W.F. Davidson

# Electric Central Station Distribution Systems

## Their Design and Construction

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# PREFACE.

THIS volume is the result of a group of articles which appeared serially in the *Electrical Age* during the years 1908 and 1909, covering various phases of Central Station Distribution Work. The preparation of these articles was undertaken by the authors because of repeated requests from young engineers engaged in distribution work for information bearing on many of the details of their work.

While there were various treatises dealing with special subjects such as low-tension networks, transmission of power, storage batteries, etc., quite fully, there appeared to be no treatise covering the general field of distribution from the standpoint of American practice to which young engineers and students could be referred. The material of the original articles revised and somewhat extended is presented in this volume. Two chapters have been included for convenient reference at the close of the book, in which are compiled such tables as are likely to be needed by the distribution engineer, together with a brief outline of the laws of electric circuits. The treatment is based upon the assumption of a general knowledge of electrical theory such as is possessed by the more advanced students of engineering and by men in practical distribution engineering work. Much of the subject matter of the book is, however, of such a nature as to be easily grasped by practical men who have not had a full theoretical training.

Distribution problems are usually capable of more than one solution, and the decision as to which is best is often determined by local conditions which cannot be made sub-

servient to general rules. It is therefore difficult to generalize upon many phases of the subject, and frequent use has been made of such qualifying phrases as "in most cases," "usually" or "under some circumstances."

The subject matter has been treated entirely from the American point of view, as the book is intended for American Engineers. European methods differ so much from those followed in America, owing to differences in the conditions under which electric lighting properties are owned and operated there, that it was not felt that their consideration would be of especial value.

THE AUTHORS.

CHICAGO, 1910.

# CONTENTS.

## CHAPTER XII.
## DISTRIBUTION ECONOMICS.



## CHAPTER XIII.
## PROPERTIES OF CONDUCTORS.



## CHAPTER XIV.
## ALTERNATING-CURRENT CIRCUITS.

# ELECTRIC CENTRAL STATION DISTRIBUTION SYSTEMS.

## CHAPTER I.

### SYSTEMS OF DISTRIBUTION.

**Series Systems.** — The arc lamp was the first practical device for converting electrical energy into light. It was developed by Brush in Cleveland in 1876 and by Thomson and Houston and others later.

The early arc systems found a ready application in the lighting of city streets. The large areas to be covered by street-lighting circuits led naturally to the series system as the most economical in first cost.

Special direct-current generators equipped with automatic regulators to maintain the current constant as the number of lamps in circuit varied, were required.

The lamps were designed to burn carbon electrodes which were consumed after about twelve hours' burning with a current strength of about ten amperes. Later, seven-ampere generators and lamps were designed in response to a demand for a less expensive light, and arc-lighting systems were extended to general commercial lighting.

Following the year 1895, the enclosed arc lamp burning carbon electrodes in an inner globe, so designed that a very small supply of air could enter, was brought to a commercial stage of development. These lamps required trimming only after sixty to eighty hours' burning, and so permitted a reduction of 75 to 80 per cent in the expense of carbons and

labor. They were therefore substituted for open arc lamp systems very generally during the following five years.

During this period of change from open to enclosed lamps, advantage was taken of the use of alternating current for arc lighting purposes. The special direct-current generator was replaced by a transformer receiving energy at the standard generator voltage of the main station and delivering it to the circuit at the voltage required to maintain a constant current of the desired strength at full load. Two general types of circuit equipment were devised for the purpose of maintaining a constant current. One consisted of a transformer of sufficient capacity to carry several circuits, with a separate choke coil for each series circuit. The position of the choke coil was controlled by weights in such a way as to make it automatic.

The other was a transformer with secondary coils arranged to be movable with respect to the primary. The position of the secondary was governed by the action of weights which were balanced against the magnetic force between primary and secondary coils. Each circuit had its own transformer in this system.

The choke-coil system was not found satisfactory on account of the fact that when grounds developed at two points on any of the circuits, a part of the lamps were shunted out, and the location of trouble was difficult.

The separate transformer for each circuit has therefore become standard for alternating-current series circuits. Series alternating-current systems using enclosed lamps are operated at 4.5 to 7.5 amperes, 6.6 being the most common current strength.

In recent years several types of flaming arc lamps have been developed. These are of the open type and have an efficiency several times greater than the enclosed arc. Some of them employ carbons impregnated with certain chemicals

which impart a high degree of luminosity to the flame of the arc. This type of lamp is operated at relatively high current densities, ten to twelve amperes being commonly used. The burning life of the carbons, however, is only twelve to fourteen hours and the carbons are more expensive than plain carbons, so that the expense of operation is much more per lamp than with enclosed arcs burning eighty hours per trim.

In another type of flaming arc the electrodes are of metal. These lamps burn sixty to eighty hours per trim and give a very high efficiency and a white light. The type known as the magnetite lamp has been used to some extent to light streets in American cities. It is applicable only to direct-current circuits, and its use with alternating-current distributing systems necessitates the use of rectifiers. This complication has retarded its introduction generally.

The arc lamp is too large a unit to be adaptable to conditions found in suburban and small towns where shade trees are numerous. Series incandescent lighting is, therefore, commonly used in such places, lamps of 32 to 50 candle power being generally employed. In some of the early systems the lamps were provided with special sockets having a choke coil in parallel, or a film cut-out which would puncture and allow the current to pass around the lamp when its filament was broken. These systems were sometimes designed to operate in several parallel series of circuits, and in other cases by series circuits direct from the station.

The series circuit controlled by an automatic regulator with twenty to twenty-five volt lamps at four to five amperes, the lamps consuming about 100 watts, is more commonly used in the operation of such systems where carbon lamps are used. The advent of the tungsten lamp gave considerable impetus to this class of service because of the great saving in energy which is made possible by its use. 60-watt tungsten lamps, operating at about four amperes, give 50 per cent more light

than the 100-watt carbon lamps at a saving of 40 per cent in energy consumption. The filaments are sufficiently rugged to insure a good lamp life, as the current strength requires a filament of large section.

**Application of Series Systems.** — The energy-consuming devices in series systems being operated at a constant current, the voltage must be varied as load is added to or removed

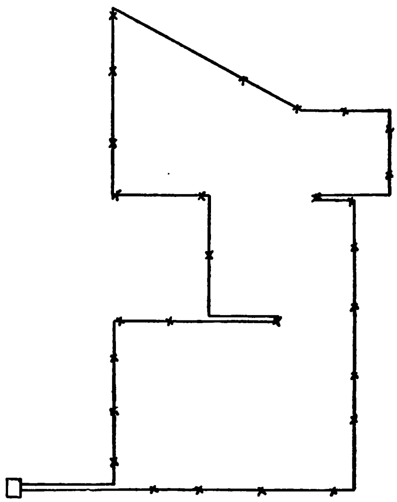


Fig. 1. Open-loop Series Circuit.

from a circuit. This limits the load which may be carried on a circuit to the maximum pressure which the apparatus and circuit fittings will withstand. The principal field for such systems is found in street and other lighting, where the lamps are scattered over a wide area with very low-load density. In such situations the distribution equipment may be installed at lower first cost than is possible with a parallel system. When the density of load is increased to a point where many circuits are required in a relatively small terri-

tory, the parallel systems become more economical. The large number of series circuits required for a heavy load in a small area requires a large investment in ducts, cables and pole space, and soon reaches a point where the value of pole space and ducts occupied by the extra circuits offsets the greater weight of copper required for a circuit to carry the same load on one of the multiple systems.

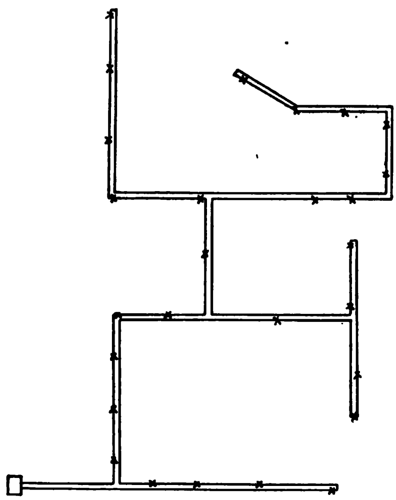


Fig. 2. Parallel-loop Series Circuit.

The design of series circuits should be carried out with a view to the use of a minimum length of conductor and yet with a sufficient number of test points to facilitate prompt location of a break. The series circuit is inherently weak in that a break at any point interrupts the entire circuit until the break can be located and closed.

The length of wire is fixed in part by the arrangement of streets which are available as routes for the circuits. A circuit may be laid out on the open-loop plan as shown in Fig. 1, or on the parallel-loop plan as in Fig. 2. The open-loop

circuit proceeds away from the point of supply through one section of the city and returns through another district. Consisting of but one wire, it is constructed with the minimum of conductor mileage. But in case of a break there is no provision for making a test to locate the trouble, and the circuit must be traversed until the break is located.

With the parallel-loop plan the wires are together so that a jumper connection can be made at any one of a number of

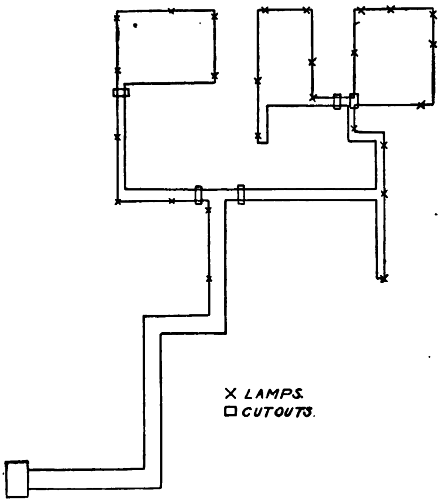



Fig. 3. Mixed-loop Series Circuit.

points. When a break occurs the circuit can be quickly closed through the remaining lamps and only those lamps on the broken loop are out. The provision of several test points on a circuit thus enables a repair man to locate the broken loop promptly and restore service on the remainder of the circuit before the break is repaired.

When continuity of service is important, as in lighting contracts which provide a penalty for lamp outages, the use of open loops should be limited to relatively small areas, as in Fig. 3, and the circuits should be equipped with convenient

facilities by which tests can be quickly made. With alternating current the use of extended open loops is likely to be the source of trouble with telephone and other signaling circuits.

**Parallel Systems.** — Parallel or multiple systems were adopted for incandescent lighting because of the possibility of operating at low pressure and of the comparative ease of control. Low pressure was desirable for safety in the consumer's premises, series systems being dangerous on account of the high voltages.

The controlling devices could be designed to suit the load, whereas in the series systems each switch must be highly insulated and of rugged construction. Incandescent lamps were much better suited to the requirements of general lighting in buildings than arc lamps, and their use extended very rapidly as soon as practical lamps were available.

The incandescent lamp was first brought to commercial perfection by the untiring patience and native genius of Edison. Together with this he developed direct-current generators and motors, fittings for underground and interior circuit construction, lamp sockets, fuse blocks and other accessories required to make up an electric lighting system.

The first electric central station for incandescent lighting in America was put into operation in August, 1882, at Appleton, Wisconsin. This was followed within a few weeks by that of the New York Edison Company. These systems were operated at about 110 volts on the two-wire plan. Direct current was used because of the lack of knowledge of alternating-current motors and transformers, and the greater adaptability of the direct-current motor to variable-speed power-using machinery.

The voltage was fixed at about 110 by the inherent nature of the incandescent lamp filament, which in the early stages

of the art could not be made to give 16 candle power at much more than 110 volts without reducing the life of the filament below commercial limits.

The excessive cross-section of copper used to deliver electricity in the quantities demanded and at the distances required led Edison to devise his three-wire system. This system was based on the operation of two generators in series with a third wire connected between the machines. This permitted the use of 110-volt lamps and yet gave the advantage of 220-volt transmission when the load was evenly divided on the opposite sides of the third or neutral wire. It thus permitted a saving in conductor copper of over 60 per cent and doubled the radius of distribution.

This system was adopted in most of the larger American cities and in many of the cities of Europe, as it was designed for installation underground, where municipal regulations required it.

The adaptability of the direct-current motor to elevator and other variable-speed power work, and the possibility of utilizing the storage battery as a reserve in case of emergency, have led to the extension of the direct-current systems in most of the larger cities.

The excessive investment required to extend low-potential lines into the outlying parts of a city and the necessity of establishing several generating stations in the large cities, thus increasing the cost of operation, soon led inventors to turn their attention to the development of alternating-current distributing systems where higher voltages could be used with transformers. The first alternating-current system was put into operation at Greenburg, Pennsylvania, in 1886, by the Westinghouse Company. Thomson and Houston added an alternating-current system to their series arc system which had been very successful, and others followed.

These systems were designed to operate at 125 to 133

cycles, 1100 volts, single-phase, and were installed in medium-sized cities where the direct current had not been established, or in the outlying parts of those cities which were being served with direct current in their central portions.

As these systems developed the demand for power service became greater and many plants needed a day load to make them profitable. The single-phase motor was not satisfactory at 125 cycles in any except the smaller sizes, and the alternating-current systems were greatly handicapped on this account. In 1888 Tesla brought out his polyphase system, in which two, three or more single-phase circuits were used with a definite phase displacement between them. This permitted the use of a simple form of self-starting motor which could be made in any desired size and was of a rugged character which made its maintenance less expensive than that of the direct-current and other commutator motors.

The Tesla system was controlled in America for a number of years exclusively by Westinghouse. His engineers selected the two-phase system as being the best suited to general distribution work, chiefly because the problem of balancing two phases was easier in a small system than the balancing of a higher number would be.

Experience had previously demonstrated that 1100 volts was too low for satisfactory service in the larger systems and 2200 volts was therefore made standard.

The design of the polyphase motors was found to be much more satisfactory at 60 cycles than at 125, and this was true of arc lamps and other apparatus having coil windings. The two-phase systems were therefore designed for 2200 volts and 60-cycle operation.

The three-phase system was developed for use in the transmission of large amounts of power at higher voltages than were used in distribution work.

Where two-phase generators constituted the source of supply the energy was transformed into three-phase for the purpose of transmission by a special method devised by Scott of the Westinghouse Company.

Later the three-phase system was adopted for distribution in some of the larger cities where the problem of balancing was not difficult because of the large number of feeders. Thus it came about that both two-phase and three-phase distribution systems are in use in the larger American cities.

The value of three-phase transmission for large amounts of energy was soon recognized by the engineers of the larger direct-current systems, who were in need of some means of consolidating numerous small steam plants into one or two large generating stations, to reduce the cost of production. This was accomplished by the introduction of rotary converter substations receiving high-tension three-phase energy and converting it to direct current at 110–220 volts for distribution.

The use of synchronous converters made desirable the adoption of a frequency of 25 cycles for the wholesale transmission. This is too low for satisfactory lighting with high-efficiency lamps, and led to the use of frequency changers in some of the larger systems where it was necessary to serve the outlying parts of the city with 60-cycle electricity.

Various transmission voltages were adopted, 6600 being used in New York, 9000 in Chicago and 13,200 in some of the other large cities. In Boston, Chicago and other cities voltages of 20,000 and upward were later adopted for use in transmission to suburban districts. As a result of this gradual development several systems of distribution are found in general use in American cities, the advantages and disadvantages of which will be considered.

**Single-Phase.** — This is a two-wire system and therefore the simplest to install and maintain of the alternating-current systems. When used for distribution in cities it is commonly operated at 2200 volts and 60 cycles, though some of the early 1100-volt, 125-cycle systems are still found in towns

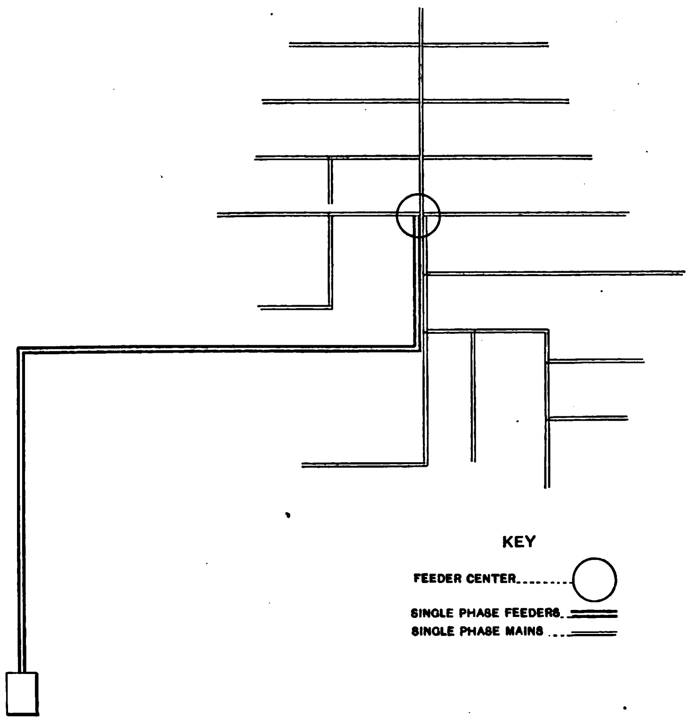



Fig. 4. Single-phase Feeder.

where growth has not displaced them. It has been adopted to some extent for interurban railways in recent years on account of the ability to use a single-wire trolley at high voltage.

The system is not suited to cities where there is a considerable amount of power load to be served, as single-phase

motors are not made for general power purposes in sizes above 40 horse power and are more complicated and expensive in their construction than polyphase motors. The general arrangement of a distributing feeder is shown in Fig. 4.

The investment in feeder conductors is somewhat more than in the three-phase systems, but the distributing mains and transformers are less expensive as there is a better diversity factor and they can be loaded to better advantage in the scattered districts.

Where the greater part of the load is lighting with only small power the single-phase system is therefore used. This is done even in systems where the feeders are operated from a polyphase generator in order to get the benefit of single-phase simplicity and economy.

**Two-phase Systems.** — In two-phase systems the generator delivers two separate currents, one of which is a quarter cycle behind the other. Hence the name quarter-phase is sometimes applied to these systems.

When the two parts of the system are operated electrically separated from each other, four wires are required. Under these conditions the circuits are virtually single-phase as far as their capacity for the transmission of energy is concerned. But where used to supply the windings of a two-phase motor through suitable transformers, the displaced phase produces a torque which makes the motor self-starting without special commutation or split-phase coils, such as are necessary with single-phase motors.

Where used for general lighting and power distribution, the lighting taps are made single-phase and balanced on the two phases with approximate equality. The four wires are carried along the principal thoroughfares and in such other places as the demand for large power service requires. Consumers using less than 5 horse power are usually required to

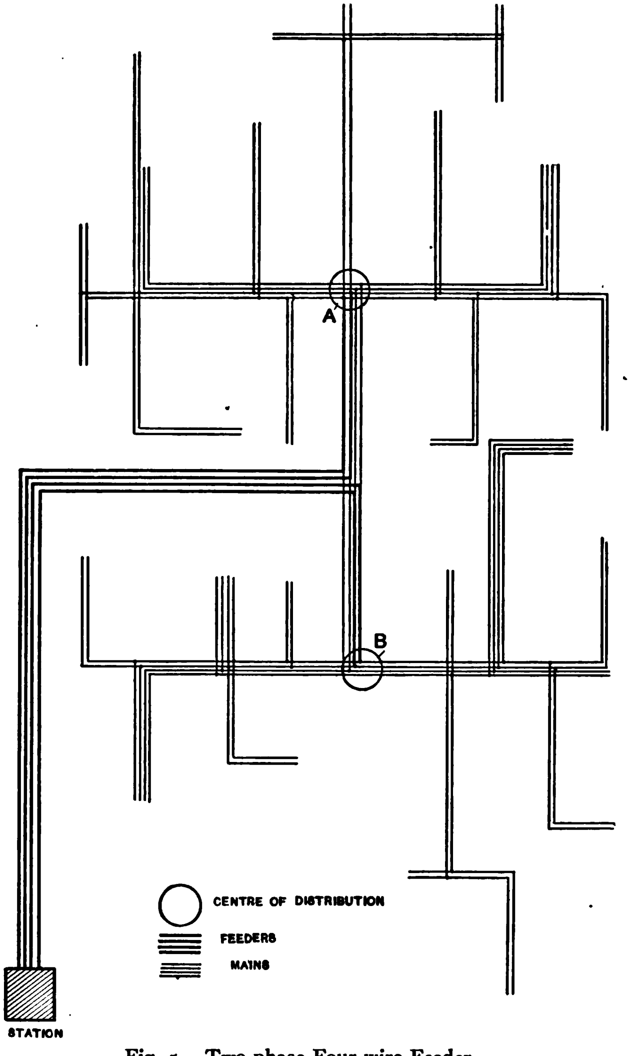



Fig. 5. Two-phase Four-wire Feeder.

provide single-phase motors, on account of the extra cost of transformers and line wire required for small two-phase service.

One method of arrangement of a four-wire two-phase feeder supplying a mixed light and power load is shown in Fig. 5. Where two terminals of a two-phase generator are connected together, as shown in Fig. 6, two of the four wires may be combined in one neutral wire and the feeder and main system reduced to a three-wire basis.

The neutral wire in such a system carries the resultant of the current in the two phases, which is 41.4 per cent more

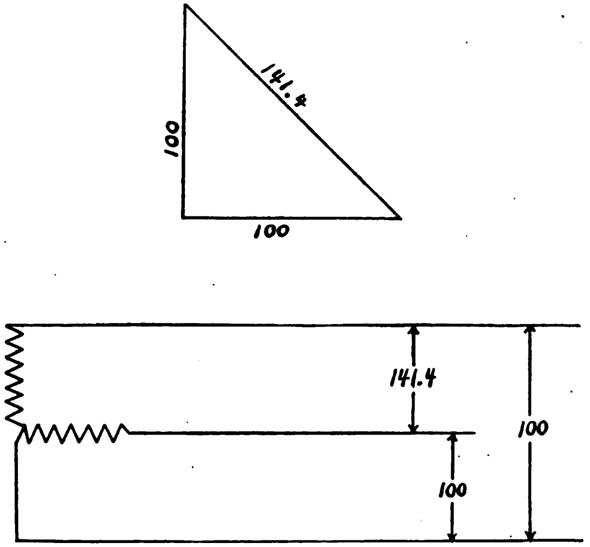



Fig. 6. Three-wire Two-phase System.

than that in the phase wires. That is, in a feeder carrying 100 amperes on each phase wire the neutral wire carries 141.4 amperes. If the same size of wire is used on each leg of the circuit, the energy loss is the same as it would be in a four-wire two-phase feeder under the same load. There being but three wires, only 75 per cent as much copper is required for this system as for a four-wire two-phase system under equivalent conditions.

In cases where feeders are so short that they are loaded up to the current capacity of the wires, it is desirable to use a larger conductor on the neutral. In such cases the saving in copper is not more than 10 to 15 per cent.

In the primary distributing mains where, for mechanical reasons, no wire smaller than No. 6 should be used, a saving of 25 per cent is generally realized.

Where two-phase systems are in use for distribution, it is usual to step up the voltage for any transmission of large amounts of energy by two transformers connected by the "Scott connection." (See Chapter VII.) This produces three-phase currents on the high-voltage side, permitting the transmission to be made on the more economical three-phase system. The reverse arrangement is sometimes used at the remote end of the line when there is a lighting load to be distributed which is not easily balanced on the three phases, as the Scott transformation scheme gives poor regulation of pressure on unbalanced loads.

**Three-phase Systems.** — Such systems are operated from generators having three sets of windings in their armatures, which are so placed that they deliver three voltage waves which are a third of a cycle apart. When these three windings are connected in series to form a closed ring the sum of the electromotive forces is always zero and no current flows unless the effective voltage is not equally balanced.

When three wires are connected at the junctions between adjacent coils they constitute a three-wire three-phase circuit which is said to be delta-connected.

When the windings of the generator are so connected that corresponding terminals of the three coils are joined together, the line wires are connected to the other three terminals and to the common or neutral point, making a four-wire circuit which is said to be Y- or star-connected. With a bal-

anced load the fourth wire is not needed and a three-wire circuit may be used for motor loads even though it is supplied from a star-connected source.

Three-wire three-phase feeders at 2200 volts are used to a limited extent in American practice for general distribution purposes. Single-phase branches are used for

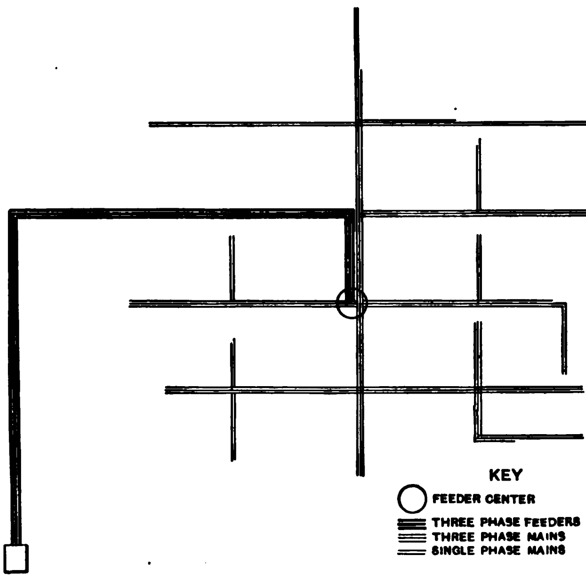



Fig. 7. Three-phase Three-wire Feeder.

the smaller lighting taps, the three-wire main system being made sufficiently general to permit a good balance to be made and to take care of the large power users as shown in Fig. 7.

Where there is an approximately balanced load the use of three-phase feeders at 2200 volts makes a saving in feeder copper of 25 per cent as compared with single-phase or two-phase four-wire feeders.

The preferable method of operation of this system in medium-sized cities is to carry the lighting all on one phase of a feeder with a smaller third wire carried only to such points as require it for power users. In manufacturing districts separate three-wire power circuits are used.

This permits the use of a single potential regulator on each lighting feeder, which permits of accurate regulation and reduces the disturbance due to power load to a minimum.

With lighting on each phase and a regulator in each leg of the feeder, the operation of a regulator affects the pressure on both phases which are connected to that leg. This makes regulation difficult, as any considerable change in the load necessitates the operation of two or more regulators.

Power users requiring from 5 to 25 horse power may be served by two transformers connected open delta, thus minimizing transformer investment.

The four-wire three-phase system has many advantages over the three-wire system, and has been adopted in most American cities which have remodeled their early equipment or developed new systems since the year 1900. This system was adopted by the Chicago central station company in 1898, and that company, with its affiliated suburban company, has the largest four-wire distributing system in America. The Boston central station company also serves a very large suburban territory on the four-wire system, and it is in use in Cincinnati, Baltimore and many other smaller American cities.

The chief point of superiority in this system is that the transmission is effected at 3800 to 4000 volts, which increases the range of distribution to nearly twice that of the 2200-volt system. The pressure from either phase wire to neutral being 2200 volts, standard 2200-volt transformers are used for both light and power service.

The lighting branches are made single phase as in other polyphase systems, but the importance of a careful balance of load on the feeder is reduced very greatly, as the neutral wire carries the unbalanced current and it is quite feasible to regulate pressure on all phases satisfactorily regardless of balance. In fact, one method of developing a four-wire feeder system consists in starting with a regulator on but one phase, all lighting being on that phase. When more lighting load is added another phase is equipped with a regulator and finally the third regulator is added. Such a method is satisfactory, however, only with a line-drop compensator in the neutral wire.

When the area to be served is so large that it is not possible to distribute all the lighting load of a four-wire feeder from one point without too much drop in the No. 6 primary main, some of the principal mains may be made larger, or the territory may be so divided that all lighting in one district is on one phase and all in the other districts on other phases. Two of the heavy feeder conductors are then run to the center of the district, thus shortening the mains and permitting each phase to be regulated for the arrangement of feeder and mains on that phase. Such an arrangement of a four-wire feeder is shown in Fig. 8.

The neutral wire in this system naturally runs near earth potential and is therefore usually grounded at the generating station. This makes it necessary to look after the insulation of lightning-arrester cases, cables at points where they join overhead wires, fuse boxes and other fittings somewhat more carefully than in other systems. It is also necessary that linemen exercise more care in working on lines where there are two or more phases present, since the difference of potential between phases is about 3800 volts instead of 2200.

This system requires one-third the copper in the feeders

which is required for a single- or two-phase system at 2200 volts, or 44.4 per cent of that required for a three-wire three-phase system at 2200 volts under equivalent conditions. This saving is somewhat offset by the increased cost of four-wire mains as compared with two- or three-wire mains.

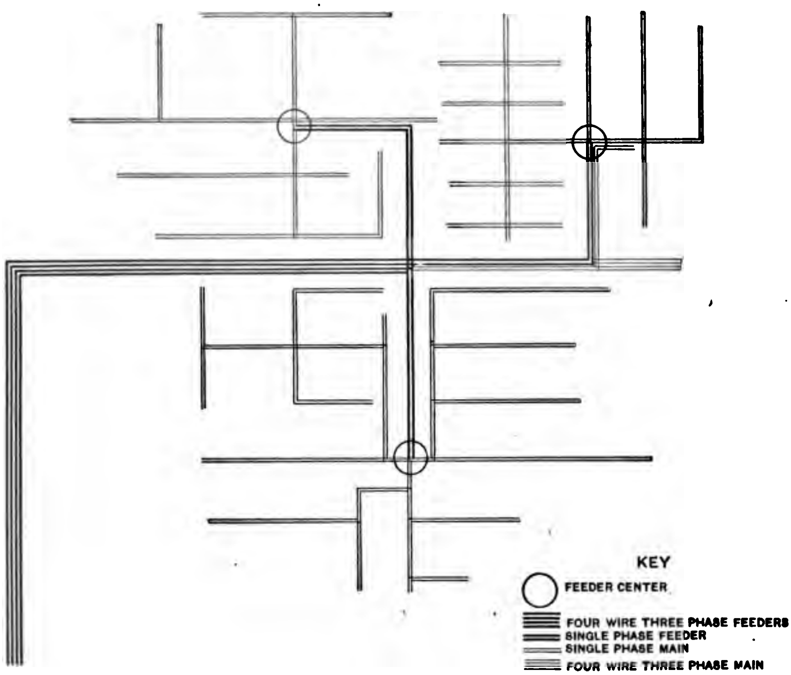



Fig. 8. Three-phase Four-wire Feeder.

The smaller three-phase power users up to 25-horsepower may be supplied from two transformers with open delta-connected secondaries as in the three-wire system. Larger users can be so supplied where the conditions are such that no disturbance is caused to lighting service by the starting current of motors.

**Direct-current Systems.** — Direct-current systems are two-wire at 110, 220 or 550 volts, or three-wire at 110–220 or 220–440 volts. Two-wire 110- or 220-volt systems are rarely used in distribution in cities or towns. In large industrial establishments, public institutions and similar situations where service is to be rendered for light and power it is usual to find 110- or 220-volt direct current. The selection of direct current in such situations is usually determined by the variable-speed power requirements. Two-wire, 550-volt power systems, which were established before polyphase systems were available, still survive in some American cities, partly because the general distribution is carried out by alternating current and partly because it would be a matter of much expense to abandon the system and exchange all the direct-current motors for others.

This voltage is high enough to permit economical distribution in medium-sized cities and the savings to be effected by a change are chiefly those incidental to the elimination of a separate set of lines paralleling the main lighting system.

Direct current at 220–440 volts on the three-wire system is distributed in two or three medium-sized American cities. The saving in copper over a 110–220-volt, three-wire system hardly compensates for the loss in adaptability to high-efficiency lamps, fans, heating appliances and similar devices.

The three-wire system at 110–220 volts (approximate) is the one in most general use. The Edison systems established in the large American cities between 1882 and 1890 are for the most part still continued in the central portions of those cities, their growth having followed the development of the commercial and manufacturing interests very closely. In the larger cities the direct current is now derived chiefly from synchronous converters, the direct-current generating machinery having been replaced by more modern

alternating-current units or held in reserve for use during the maximum-load period of the winter months.

The scattered mains originally laid have grown to heavy networks with feeders supplying them at frequent intervals and service connections into almost every building.

The direct-current system is maintained for the most important service because of the demand for variable-speed motors above referred to, and because of the availability of the storage battery as a reserve.

With storage batteries located at important points on the system, the interruption of service to a converter substation may occur with little or no interruption to the direct-current service. In case of a general interruption affecting several substations partial service may be maintained for a sufficient time to permit converters to be synchronized and gotten into operation again. There are several large direct-current networks in America which have not suffered a complete shutdown during ten years.

The mains from which service is taken in the underground portions of direct-current networks are rarely smaller than No. 0 or larger than 1,000,000 c.m. In the heavily loaded districts 350,000 to 750,000 mains are commonly found. The feeders vary from 4/0 to 2,000,000 c.m. The common sizes in the denser parts are 750,000 to 1,500,000 c.m. The network is joined at street intersections through fused junction boxes. The main in each block, therefore, has a double feed, which enables it to carry a heavy load at any point more satisfactorily than if there were no network arrangement. This also assists in maintaining continuous service, as the melting of a fuse at either end may merely drop the pressure without blowing the fuse at the other end. In case of a burnout of a main the fuses at both ends are usually blown, thus isolating the section and preventing the extension of the trouble to other blocks.

**Combination Systems.** — A combination of alternating with direct current, or of two differing alternating systems, is usually found in the larger cities.

Direct-current systems are supplied by converting alternating current, in many cases, and 60-cycle systems are supplied in part from a 25-cycle source of energy. When the generating system is operated at 60 cycles the direct-current

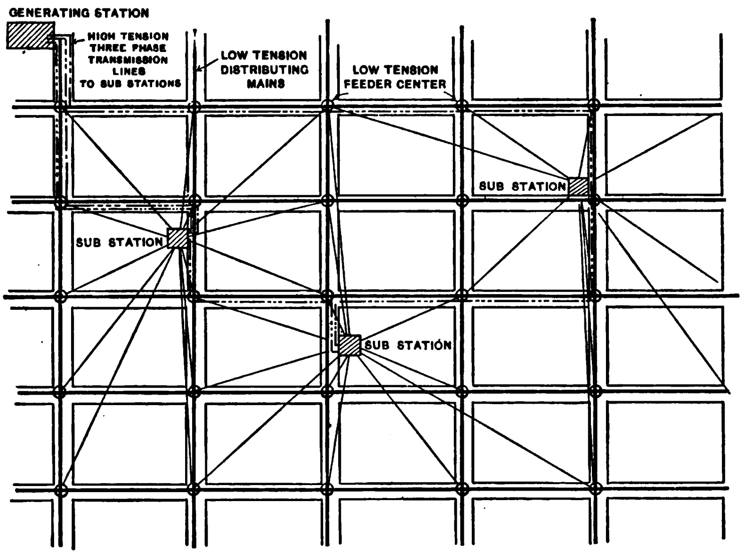



Fig. 9. Low-tension Network.

service is derived through motor generators, as in the Boston and Philadelphia systems. Where 25-cycle energy is generated the direct-current supply is derived through transformers and synchronous converters.

The superior economy of the synchronous converter as compared with the motor generator outweighs its lack of stability in an emergency where the larger part of the load generated is distributed in the form of direct current. In

cities like New York and Chicago synchronous converters are therefore used in preference to motor generators.

The portion of the load which is distributed as alternating current in such cities must be generated by separate 60-cycle steam-driven generators or by 25-cycle motor-driven generators, since 25-cycle current is not well adapted to general lighting and power purposes and is not as salable as 60-cycle electricity.

When the 60-cycle distribution forms a considerable part of the whole, electricity is preferably generated at this frequency and the portion required in the form of direct current is secured through motor generators. The selection of the transmission frequency is therefore usually governed by the relative amount of direct- and alternating-current load which is to be distributed. A typical arrangement of substations and direct-current network is illustrated in diagrammatic form in Fig. 9.

## CHAPTER II.

### TRANSMISSION AND CONVERSION.

In the development of a distributing system, the radius of transmission from the point of supply tends to increase as the population grows. After a time the number of feeders to certain districts remote from the generating station becomes such that the transmission may be effected at higher voltage to much better advantage. Such transmission involves transforming and regulating apparatus at a point remote from the generating station, which in turn requires a building and other accessories, and the result is a substation. The substation involves an investment in real estate (or a rental charge), transforming apparatus, switchboard, etc., and an operating expense for attendance and repairs. On the other hand the feeders running into a district occupy valuable duct or pole space and require a large investment in conductors.

**Establishment of Substations.**— It therefore becomes profitable to establish a substation when the amount required to pay fixed charges on the substation investment and its operating expenses is about equal to that required to meet the fixed charges and maintenance expense on the feeder equipments which would be required if a substation were not installed. In a growing system it may be advisable to anticipate this point somewhat and install the substation earlier, in order to avoid the loss due to the installation and removal of feeders which are transferred to the substation after but a few years' service.

The point at which the balance between substation cost and feeder cost is struck varies widely with different systems and classes of construction. In a low-tension direct-current underground system the number of substations is usually greater than in an alternating system with 2200-volt mains, because of the shorter radius of action in low-tension systems.

There are also many local conditions to be considered, and two problems are rarely, if ever, identical in every particular. With a given class of construction, the radius of distribution and therefore the number of substations is fixed first by the voltage of distribution and second by the load density.

With a feeder loss of 10 per cent at maximum load and a current density of 1 ampere per 1000 c.m., the length of a feeder is approximately one mile for each 1000 volts of feeder pressure. On this basis the radius of distribution at 220 volts is .22 mile or 1100 feet, and at 2200 volts it is 2.2 miles. There are usually some feeders which are longer than this on which the loss runs higher. When these become sufficiently numerous an additional substation becomes desirable.

It is sometimes necessary to establish a substation on account of a large block of load such as an amusement park, large retail store, manufacturing plant or other similar enterprise.

**Transmission Systems.** — The selection of a system of transmission for the wholesale distribution of energy from the generating station to substations is a matter of great importance. The three-phase system is used almost universally for this purpose, owing to its inherent economy of copper, reduced cost of generating apparatus and its adaptability to rotary-converter and motor-generator work.

**Voltage.** — The voltage employed in the transmission system should be high enough to permit the economical supply

of the most remote sections of the city and should preferably be capable of reaching suburban substations.

In the larger cities where the loads to be transmitted are very great in proportion to the distance, it is desirable to use a voltage high enough to keep the size of transmission cables within reasonable limits. Voltages of 20,000 to 25,000 have been found desirable in some of the larger cities in connection with transmission to suburban substations, though lower voltages are much more usual.

The generator voltage should be such that it can be used for local distribution near the station if desired. There is no advantage in first cost in the use of generators wound for the transmission voltage except in sizes less than 1000 K.W.

The voltage selected should be one which is standard with manufacturing companies, in order to secure lower first cost and to facilitate delivery of coils and other apparatus which may be required for repairs.

**Frequency.** — In American practice two frequencies are standard for transmission purposes, namely, 25 and 60 cycles per second. Other frequencies, such as 30, 40 and 66 cycles, are in use to a limited extent, but are not considered standard. 25-cycle current is found preferable when the major part of the energy transmitted is converted to direct current for distribution. This is so because of the fact that rotary converters are much more stable in their operation at the lower frequency than they are at 60 cycles.

Where transmission is effected by underground lines the charging current of the cables at 60 cycles becomes an important factor in a large system and may result in high potential surges in the transmission system in connection with switching operations, synchronizing and disturbances due to the occurrence of short circuits or grounds.

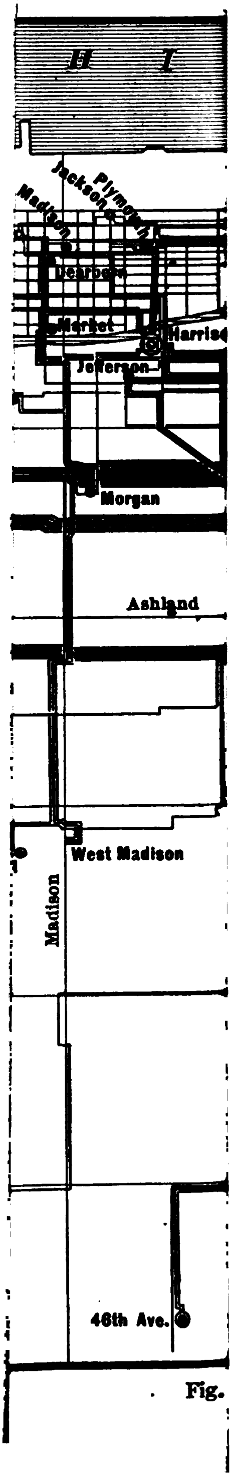

H
I
Plymouth
Jackson
Madison
Dearborn
Market
Harris
Jefferson
Morgan
Ashland
West Madison
Madison
46th Ave.

Fig.

25-cycle energy, however, cannot be used for arc lighting and is not satisfactory for incandescent lighting, except out of doors, owing to the noticeable flickering of the light. It is therefore necessary to convert the energy to 60 cycles for distributing purposes where 25-cycle energy is used in transmission. 60-cycle motors and transformers are less expensive than 25-cycle, which further favors the use of the higher frequency for distribution.

**Reserve-line Capacity.** — In a system embodying a number of substations and perhaps more than one generating station, the design of the transmission lines supplying each substation, with reference to continuity of service, becomes a matter of great importance. All important substations should have at least two sources of supply. In some cases the geographical arrangement permits one line to be looped into the substation nearest the power house, so that the line from this substation to the farther one becomes a tie line. Such a tie line, when provided with a suitable arrangement of switches and bus connections, forms a very desirable reserve supply for both substations, as it can be fed from either end. In other cases it is preferable to get the reserve supply by tapping the nearest available line.

In a low-tension direct-current system with storage-battery reserve, the smaller substations which are operated only during the heavy-load period are sometimes so located that the expense of having reserve transmission-line capacity is so great as not to be justifiable.

The development of a portion of the transmission system in the city of Chicago up to 1909 is illustrated in Fig. 10. It will be noted that in this system there are three generating stations producing 25-cycle 9000-volt current. This system is somewhat different from that of other large cities in that several of the direct-current substations are used exclusively

for the supply of 600-volt current to street-railway companies and elevated roads. It will also be noted that practically all of this system is underground, there being approximately 400 miles of three-conductor 9000-volt cable in service.

**Classes of Substations.** — Substations may be divided into two general classes according to the kind of electricity they are designed to distribute — viz., alternating current and direct current. Alternating-current substations are of two general types, transformer and frequency changer.

Direct-current substations are of three types, synchronous-converter, motor-generator and storage-battery.

**General Principles.** — The design of a substation building and equipment must be made with a view to economy of operation, facility of repair and construction work, security of the service and employees, and a minimum first cost consistent with these conditions and with the importance of the service. Where growth is probable, due regard must be had for extensions of building or equipment, or both. The character of the building and equipment is fixed by the kind of service to be given, whether alternating- or direct-current, at high or low tension.

The economy of operation should be as high as possible, as the added expense of maintaining an attendant must be offset by the superior efficiency of the substation system as compared with feeders direct from a generating station.

The arrangement of apparatus with regard to the work of construction and repair men should be such as to minimize first cost and operation. Proper provision for repairs will shorten the time of a shutdown very materially, thus saving loss of income and injured reputation for reliability. No design is permissible which involves unusual risk of interruption to the service. The first cost must be kept within proper

limits, since fixed charges on the investment form a considerable part of the cost of electricity supply and must be as low as possible.

**Transformer Substations.** — Transformer substations are used where the frequency of the distributing system is the same as that of the transmission lines, but voltage transformation is necessary. Such a substation consists essentially of incoming transmission lines, line and transformer switches, transformers, distributing switchboard, feeder regulators, switches, instruments, etc., and outgoing feeders. In its simplest form it may embody but a single transformer and switches without instruments or other accessories, except perhaps lightning arresters, the pressure regulation being affected at the generating end of the line by the use of line-drop compensators. Such an outfit does not necessarily require a building and may very satisfactorily be used, up to 150 or 200 K.W., to supply a remote residence section where no large power service is required. Where the load is larger there is likely to be a demand for three-phase power, in which case three transformers may be supplied by a four-wire feeder, in a very inexpensive building without other accessories than disconnecting switches on each side of the transformer and lightning arresters. The four-wire transmission line may be regulated by regulators on each phase, at the generating end, and the distributing feeders carried to several adjacent suburbs. This system has been used for outlying suburbs in Chicago at 4400–7600 volts for loads up to 600 K.W., power and lighting being served with the same degree of facility that is possible with similar business located within the range of the distributing feeders operating from the point of supply direct.

When the number of feeders from a substation is such that regulation must be secured at the substation, it is necessary

to equip the feeders with potential regulators and maintain an operator on duty during the hours of heavy load. If there is much day power load an operator should be on duty about 16 hours a day as a rule. The addition of regulating equipment and an operator necessitates a higher grade of building, and this is usually warranted by the importance of the service at this stage of development.

The usual distributing voltage in alternating-current systems being about 2300 volts, it will facilitate the discussion to assume a practical example of this class and to consider the various elements which require treatment in the design.

Assume that a substation receiving energy at 60 cycles, 13,200 volts, is to deliver it at 2300–4000 volts on the four-wire, three-phase system. The maximum load of 2400 K.W. is to be delivered by four feeders. The building is to be located on a fifty-foot lot on a side street near the electrical center of the district which it is to supply. The value of the equipment and the importance of the service demand a fireproof building. The external appearance will be governed largely by the character of the neighborhood. If it is in a manufacturing district it may take the nature of a factory building. If in a residence district it should be given more of the appearance of an apartment building. In suburban territory where land is plentiful, it is usual to finish the building on all sides and surround it by lawn and flower gardens. Where it is desirable to combine the substation building with a district office, it is usual to locate it on a business street, placing the office building in front and the substation in the rear or in a basement.

The interior of a transformer substation building is illustrated in Fig. 11.

The arrangement of the interior of the building is necessarily restricted in many cases by local conditions which do not permit an ideal arrangement of the apparatus, but as

such cases require special treatment, this discussion will proceed upon the assumption of a building of ample size and proper shape to permit of an unrestricted design.

The arrangement of apparatus will, in general, be most desirable when it is such that the flow of energy progresses from entrance to exit with the least number of changes in direction. This makes the length of cables a minimum, tends to

Fig. 11. Transformer Substation.

avoid crossovers, facilitates repairs and results in economical operation.

In the case in point the arrangement suggested is illustrated in Fig. 12. It will be noted that the transmission lines enter at one side of the building, pass through their oil switches to a bus bar, thence through a smaller oil switch to the transformers. From the transformers the 2300–4000-volt energy passes through switches to the bus, from which it is distrib-

uted. The outgoing feeders pass through switches and potential regulators and leave the building at the other side.

Two incoming lines should be provided if continuous service is important. This necessitates a tie switch between

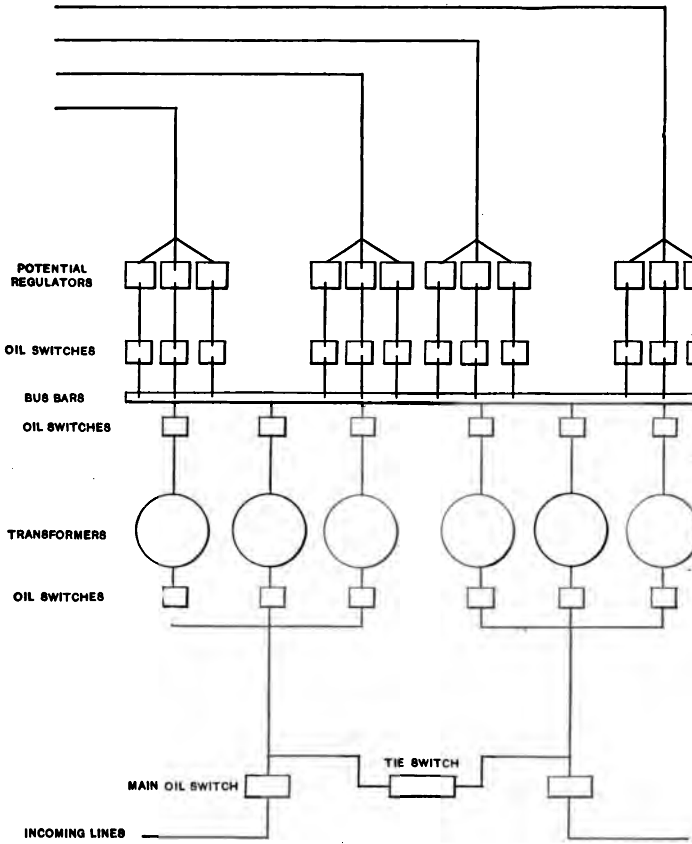



Fig. 12. Component Parts of Transformer Substation.

them so that the whole load can be carried on either line.

Switches must be provided on each side of the transformers so that they can be isolated if necessary.

The 2300–4000-volt bus is preferably made double to permit repairs or alterations to be made without interrupting the service. It is also useful at times in permitting longer feeders to be carried at a higher bus pressure or from a different source of power.

The use of an auxiliary bus requires double-throw switches throughout and adds to the first cost of the station. It may sometimes be omitted in small substations where there is a single incoming line and only two or three outgoing feeders.

The outgoing feeders leave the bus through single-pole switches and pass through the regulators for the control of the pressure. With a three-wire system it is usual to employ three-pole switches, but in a four-wire, three-phase system each phase is independent and it is not desirable to open the entire feeder when trouble occurs on one phase only, as is often the case.

In the arrangement suggested in Fig. 12, the line and high-tension transformer switches occupy space next to the wall, with an aisle between them and the transformers of such width as to permit ready access for inspection, repairs or the replacement of a transformer. The 2300–4000-volt busses are at the rear of the board, with an aisle between them and the regulators so that they may be accessible. The regulators are motor-operated and are placed near the wall in the path of the outgoing feeders. The control switches for the regulator motors are on the switchboard close to the voltmeter, so that the operator may control the pressure while watching the voltmeter. Less expensive hand-controlled regulators are sometimes installed where the arrangement is such that the handles can be extended to the front of the switchboard.

The high-voltage conductors between oil switches and busses are commonly insulated with varnished cambric and sup-

ported on suitable insulators. The lead sheaths of incoming lines and outgoing feeders are terminated in suitable bells or pot heads, which serve to dissipate any static charge which may tend to accumulate and to exclude moisture from the insulation of the cable.

The arrangement suggested in this assumed case is of course an ideal one, since no limitation of space or other local conditions are imposed. In many cases the required floor space is not available or is too valuable for other purposes to justify its use for substation purposes. Under such circumstances, floor space may be economized by placing the pressure regulators on a gallery above the switchboard, or in the basement. The latter arrangement brings them in line with the outgoing feeders, and is preferable if the basement is of suitable depth and size to give room to handle and install the apparatus. With a room which is not long enough to permit the transformers to be set in a row it may be necessary to try various groupings of the oil switches and transformers until the best arrangement is found. Each proposed arrangement must be considered with reference to the disposition of the apparatus and connections in the basement as well as on the main floor. No design is justifiable which makes a nice-appearing installation of the main floor but which necessitates dangerous conditions elsewhere in the building.

**Switching Apparatus.** — The switches on the incoming line must be capable of opening the entire load under emergency conditions, and should therefore be of the oil break type with separate fireproof compartments for each pole. These switches must be equipped for protection by reverse-current relays, if the incoming lines are operated in parallel, which necessitates a set of current transformers on each line. Suitable space must be provided for these near the switch, as well as for the relays.

The switches must be operated by alternating current with auxiliary hand control in the absence of any source of direct current for this purpose. The switches controlling the transformers may be of a smaller type of oil switch, the transformers being arranged so that they can be disconnected entirely on both sides. The switches on the line side should be protected by overload relays, while those on the 2300-volt bus should be protected by reverse-current relays to guard against the failure of a transformer coil.

These switches may be of the type which is closed against a spring by hand and opens automatically when tripped by the relay. The relays for primary and secondary of the transformers may conveniently be located on the switchboard panel which carries the secondary switch. The current transformers should be located in a safe place where they are convenient to the leads of the main transformers.

The switches on the outgoing four-wire feeders should be of the hand-closing, spring-actuated type of circuit breaker. Fuse protection is sometimes used on 2300-volt feeders, but it is not as satisfactory as circuit breakers, because of the longer time required to restore the service when a fuse blows, the greater likelihood of fuses blowing unnecessarily under heavy loads, and the difficulty of designing a fuse block which will not be injured by the operation of the fuse within a comparatively short time.

Outgoing feeder switches should have a capacity of 150 to 200 amperes at 2300 volts. It is not desirable to load distributing feeders any more heavily than this, and in many scattered districts 100 amperes is as much as can be properly distributed from the feeder end.

**Transformers.** — The transformer equipment may be of the air-blast, oil-cooled or water-cooled type. Oil-insulated transformers are less subject to puncture by lightning or

high-potential surges and are usually used with overhead lines for this reason. Air-blast transformers are the least expensive in first cost, but involve apparatus and ducts for the fresh-air supply. In a large substation this may become a serious difficulty owing to the space required for the air ducts. The circulation of water or oil permits more rapid cooling and is therefore desirable in the larger units in order to keep the size and first cost of the transformer within reasonable limits.

Where floor space is limited, air-cooled units are desirable, as they are smaller in external dimensions and are designed with a view to occupying a rectangular floor space of very small area.

With oil-cooled units of 500 K.W. and upward it is advisable to provide drains to a sewer for the transformer oil so that in case it should become ignited it could be drained off to assist in extinguishing the fire.

With very high voltage transmission systems it is usual to install the transformers in separate compartments to guard against the spread of an arc or flames from burning oil to adjacent transformers. With units of 2000 K.W. and larger this expense is usually justified in view of the importance of the service and the investment involved.

**Reserve Capacity.** — The selection of the size and number of units for a substation is a matter of great importance from both operating and investment standpoints.

The units should be large enough to give some reserve capacity, and numerous enough to leave sufficient working capacity in case a unit fails

In the three-phase station used here for illustration, the use of two units on each phase would result in a reduction of 50 per cent in capacity on one phase if a unit fails. If the units are selected with a reserve capacity of 20 per cent, the

load can be carried by running one unit at about 50 per cent overload until a spare unit is put in place of the defective one. Where the service is important a spare unit should be available at all times for emergencies. In a system with several substations, two or three sizes may be standardized, one of each being carried as reserve. Where there are several substations it is sometimes possible to secure reserve through tie lines from adjacent stations which may have spare capacity.

**Switchboard.** — The switchboard should be located in a position where the instruments may be readily observed by the operator, and at a sufficient distance from the wall to give reasonably good access for construction and repair work. It carries no high-tension connections except where the feeder switches are of the hand-operated type, in which case they are preferably mounted on the panel with the instruments. Where remote-control switches are employed, the switchboard carries only secondary low-pressure wiring, such as instrument connections, remote-control circuits, compensator circuits and the like. Such a board may be located in convenient parts of the room where it is accessible to the operator. The operation of remote-control switches should be indicated to the operator by pilot lamps of red and green on the operating board.

Each feeder should be provided with an ammeter as a means of indication of the load carried and a voltmeter in connection with a line-drop compensator to indicate the feeder end pressure to the operator. A power-factor indicator is a desirable accessory on the main bus.

The transformer panels should be provide with ammeters and a bus voltmeter for each bus and phase. The control wiring for the transformer switches is also brought to the transformer panels.

The design of the switchboard should be carried out with a view to making as economical an arrangement of the apparatus as is consistent with safety of installation and operation.

The arrangement of the wiring for instruments, relays and similar apparatus should be carefully made with a view to making it secure from failure, accessible for testing and repair work, and neat in appearance. Where a number of wires are grouped on one or two panels, the use of terminal boards for testing and repair purposes is very desirable. These should be placed so that an instrument adjuster can get at them conveniently without disturbing the connections at the instrument terminals.

The switchboard should be of fireproof materials, marble or slate on angle iron frames being the most commonly used construction. The arrangement of switches and bus connections should be such as to minimize the danger of the spread of an arc. The location and arrangement should permit of necessary extensions which may be required in connection with the addition of feeders from year to year.

**Frequency-changer Substations.** — The essential difference between the frequency-changing substation and a transformer substation arises from the presence of motor generators. The in-coming lines with their high-tension switching equipment and outgoing feeders with their switchboard and regulators are practically identical under equivalent conditions of load and space available in the two kinds of substations.

The motor generator outfit requires about the same floor space as an equal capacity in single-phase transformers when the motor is wound for the transmission voltage and the two machines are mounted on a common bedplate with a short shaft and two bearings. When designed in the vertical form there is some saving in floor space in the larger units.

Where the transmission is at a pressure too high for the motor windings direct, the motor generators require transformers and this increases the required floor space of the substation very materially.

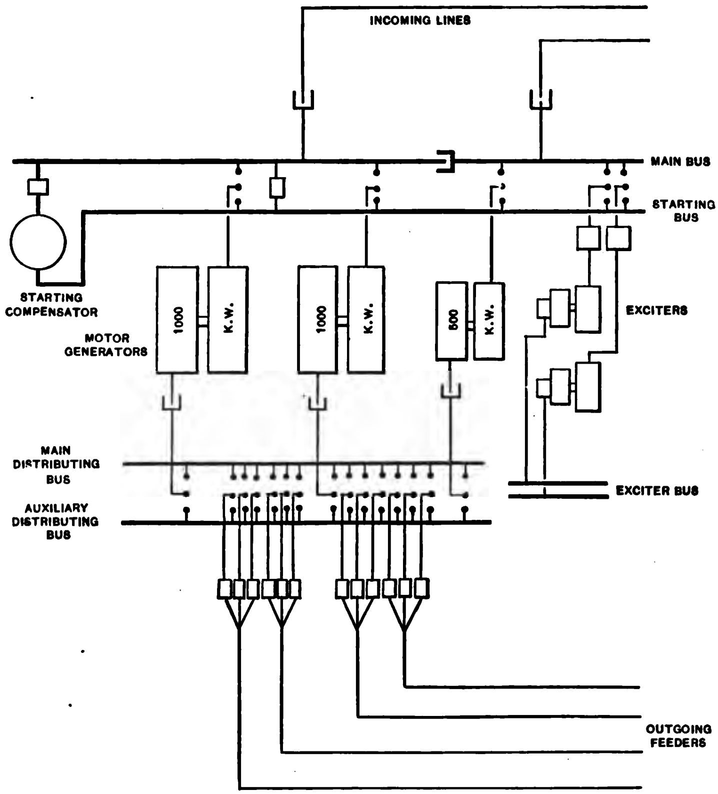



Fig. 13. Frequency-changer Substation.

With a substation of 2500-K.W. capacity with synchronous motor generators taking energy at the line voltage the units should consist of two 1000-K.W. and one 500-K.W. and the arrangement might be made similar to that shown in Fig. 13.

It will be noted that this substation includes exciters for the fields of the motor generators and a high-tension starting bus fed by a reactance coil, for use in bringing the synchronous motors up to speed, at reduced pressure. A single reactance coil is provided together with double-throw switches on the motors so that any motor can be thrown to the starting bus and started from the one starting coil, the cost of the bus and double-throw switches being less than that of extra reactance coils. Duplicate exciters driven by separate motors at the transmission frequency should be provided, as they must be started at times when the station is shut down, and reserve capacity must be available in case repairs become necessary on either unit. In some cases it may be sufficient to have two exciter units separately driven, with others driven by the main units.

Where the presence of direct current is taken advantage of for automobile charging, traveling crane or hoist service, it is important that the direct-current bus be divided so that the fluctuations of load will not affect the generator fields and so produce pressure variations throughout the entire system. Where Tirrill regulators are used, it is also desirable to have them control the pressure on the 60-cycle generators only. This necessitates the use of a separate direct-current bus for the synchronous-motor excitation.

The exciter units being less than 100 K.W., it is usually not practicable to use motors wound for the line voltage to drive them. This requires a set of transformers and permits the use of low-voltage induction motors which are less sensitive to shocks on the transmission system. The entire control of the exciter may thus be placed on a low-voltage switchboard.

One of the chief points of interest about such a substation is the method of starting and synchronizing the motor generator sets. When a unit is to be put in service it is connected

to a starting bus supplied by an autotransformer at 40 per cent of the transmission line pressure. The switches controlling the direct current for the fields of the motor are left open. The oil switch controlling the motor is then closed to the starting bus and the unit begins to revolve as a hysteresis and induction motor. When the unit is at approximately synchronous speed the field is excited, thus drawing the unit into step as a synchronous motor. This usually causes a rush of current for a very brief interval of time, as the machine is likely to be out of phase at the instant the fields are excited.

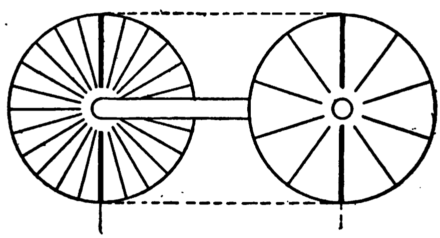


Fig. 14. Poles of Frequency Changer.

When the conversion is from 25 to 60 cycles this usually does not complete the operation of synchronizing, as the 60-cycle generator is not necessarily in phase with its bus when the 25-cycle motor has been synchronized. The ratio of the number of field poles on the 25-cycle motor to those on the 60-cycle generator must be as 25 is to 60 or as 10 is to 24. When a 10-pole field is mounted on the same shaft with a 24-pole field, as is usually the case in a 25–60-cycle frequency changer, only one set of poles on each field can be lined up in the same radial plane. In Fig. 14, the poles which are aligned in the same radial plane are represented by the heavy diameters. When the 25-cycle machines are synchronized, any of the five sets of poles on the incoming machine may fall into step with the poles represented by the heavy line on the

operating unit. When the 25-cycle machine has fallen into step, as in Fig. 15, on the pair of poles next to the one represented by the heavy line in Fig. 14, the incoming 60-cycle machine is held out of phase with the operating unit as shown by the dotted vertical line. If the rotation is counterclockwise, the machines can be brought into phase by removing the supply of energy from the incoming machine and allowing it to slip back one pair of poles, or 36 degrees, until the heavy lines are in phase with each other. The machines are then in phase on both 25- and 60-cycle ends. A special synchroscope is usually employed which has five points corre-

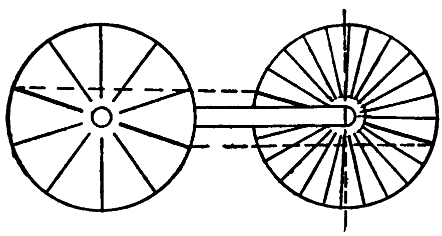


Fig. 15. Displacement of Phase Frequency Changer.

sponding to the five positions in which it is possible to bring the 60-cycle machines into synchronism.

If in synchronizing the 60-cycle pointer takes position No. 4, it is necessary to "slip poles" four times before the 60-cycle machines can be thrown in parallel.

These complications do not arise in synchronizing a single frequency changer with a 60-cycle generator driven by a prime mover, as the prime mover can be adjusted to bring it into phase.

A typical substation of this class is illustrated in Fig. 16. The two horizontal units are rated at 1000 K.W. each, while the vertical unit is rated at 2000 K.W. The exciter for the vertical unit is mounted at the top, the armature

being carried on the main shaft. In this substation the exciter for the 2000-K.W. unit is provided with suitable switching arrangements which permit its use as a direct-current motor in bringing the unit up to speed. This relieves the transmission system of the shock of starting as an induction motor. Direct current is supplied from one of the other

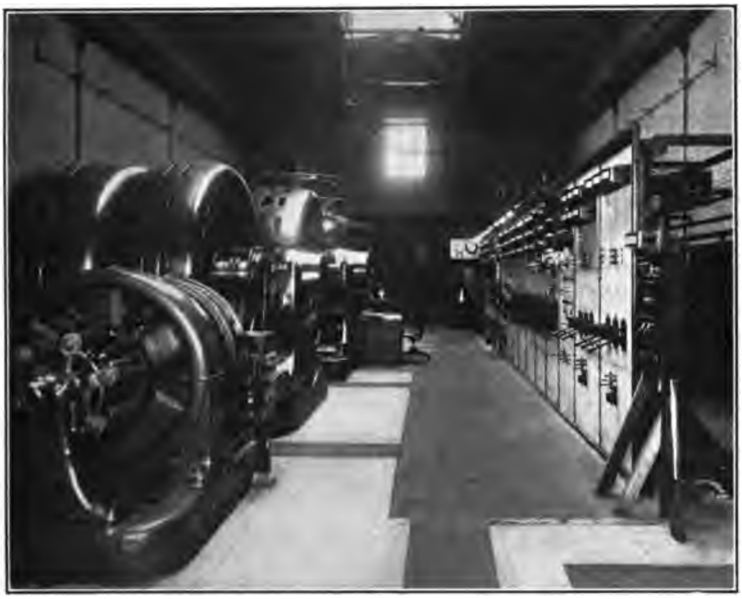


**Fig. 16. Frequency-changer Substation.**

exciter units for this purpose. The switchboard containing the controlling apparatus for the exciter system, 60-cycle generators and feeders appears at the right. The vertical unit is carried on a special roller step-bearing. Several of these 2000-K.W. units are in service in the city of Chicago, in substations where the saving in floor space, improved efficiency and slightly lower first cost made their adoption desirable.

**Direct-current Substations.** — The direct-current substation receives high-tension alternating energy and converts it to low-tension continuous energy, or, in the case of the battery station, receives continuous low-tension energy and delivers the same, the function of the battery being to store energy for use in an emergency.

Converting direct-current substations are of two general classes, motor generator and synchronous or rotary converters. In systems generating energy at 25 cycles, the synchronous converter is employed very generally because of its greater efficiency and lower cost as compared with motor generators. Where the generating system produces 60-cycle energy the synchronous converter is not employed because of its lack of stability, but the direct-current supply is derived from motor generators. Both synchronous and induction motors are employed. The synchronous motor is very desirable because of the ability to control the power factor so as to offset the effect of inductive loads elsewhere in the system. It is, however, subject to the disadvantage that it is thrown out of step rather easily by disturbances in the transmission system. Thus a short circuit at some remote point may cause the synchronous motor to fall out of step and shut down when it should not do so.

The induction motor having no power-factor control is at a disadvantage in that respect, but it is not easily thrown out of phase sufficiently to cause it to be shut down and therefore has much more stability than the synchronous motor. The efficiency of the synchronous motor is somewhat better than that of the induction motor.

It is therefore usual in the larger 60-cycle distributing systems, to equip direct-current substations with a mixture of synchronous and induction motors. This permits control of the power factor so that the full generating capacity is available and yet retains the necessary degree of stability in times of emergency.

The comparative efficiencies and costs of a few principal sizes of motor generator and synchronous converter sets, as presented by Allen in a paper before the Association of Edison Illuminating Companies in 1908, is presented in Table I.

TABLE I. — EFFICIENCIES.

| K.W. | Per cent load. | 25 Cycles. | | | 60 Cycles. | | |
|---|---|---|---|---|---|---|---|
| | | Syn. mot. gen. | Ind. mot. gen. | Syn. converter. | Syn. mot. gen. | Ind. mot. gen. | Syn. converter. |
| | | Per cent. | Per cent. | Per cent. | Per cent. | Per cent. | Per cent. |
| 300 | 100 | 84 | 85.3 | 89.5 | 86.7 | 84.8 | 88 |
| 300 | 75 | 82.3 | 83.3 | 88.5 | 85 | 82.3 | 86.7 |
| 300 | 50 | 77 | 79.8 | 86.5 | 81.7 | 79 | 82.5 |
| 500 | 100 | 85.5 | 86.8 | 90.8 | 87.8 | 86.3 | 89 |
| 500 | 75 | 83.7 | 84.8 | 90.3 | 86 | 84.3 | 87 |
| 500 | 50 | 79.5 | 82 | 88.3 | 83 | 81 | 83 |
| 1000 | 100 | 87.5 | 87 | 91.8 | 87.8 | 87 | ........ |
| 1000 | 75 | 86 | 85.8 | 90.5 | 86 | 85.3 | ........ |
| 1000 | 50 | 82.2 | 82.3 | 90 | 83 | 82 | ........ |

APPROXIMATE COST PER KILOWATT.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 300 | ...... | $26.20 | $26.35 | $25.15 | $25.75 | $25.85 | $25 |
| 500 | ...... | 24.70 | 24.35 | 22 | 23.2 | 23.40 | 22.7 |
| 1000 | ...... | 20.25 | 19.85 | 19.80 | 19.45 | 19.50 | ........ |

FLOOR SPACE, SQUARE FEET.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 300 | ...... | 80 | 80 | 91 | 67 | 67 | 96 |
| 500 | ...... | 122 | 122 | 131 | 110 | 110 | 150 |
| 1000 | ...... | 136 | 136 | 170 | 140 | 140 | ........ |

A study of this table shows that all sizes of 25-cycle motor generators are about 4 per cent less efficient than synchronous converters of equal capacity. The 25-cycle induction motor sets are slightly more efficient than the synchronous motor sets. The synchronous converter costs less in all sizes than the motor generator. At 60 cycles the synchronous motor sets are slightly more efficient than those driven by induction

motors, while the converter is about 3 per cent more efficient than either.

The cost is nearly the same per kilowatt for motor generators as for converters at 60 cycles. These figures apply to converters and motor generators having interpoles. The converter costs include air-blast transformers.

**Low-tension Switchboards.** — The direct-current distributing equipment being operated at low potential is radically different from the 2200-volt alternating-current equipment above described. The bus bars are of bare copper about half an inch thick and from three to six inches wide, built up, with air spaces between for radiation, to the required number to carry the current. These are mounted at the back of the switchboard so that the connections to the generator and feeder switches may be as short as possible. The chief consideration in the design of such boards is an arrangement using a minimum length of copper, as it is necessarily of heavy cross-section. The board should, therefore, be as short as possible, but the opposite polarities should not be so close as to endanger the service in case a short circuit is made.

The arrangement shown in Fig. 17 and Fig. 18 accomplishes these objects very effectively. The upper row of switches are all of one polarity and the lower of another. The neutral conductor need not be switched and is connected direct to the neutral bus. The separation is ample and the length of bus-bar copper per feeder is about 6 inches for each pole of the bus.

This close spacing necessitates the use of the edgewise type of ammeter, an instrument being placed on each side of the three-wire feeder. The location of the polarities is usually standardized for the sake of uniformity. That is, the positive bus is placed above or at the right, and the negative below or at the left, or *vice versa*. Separate voltmeters are

not necessary for each feeder in direct-current networks, but the pressure wires brought from the feeder ends are terminated in a multiple-point switch so arranged that the pres-

Fig. 17. Rear of Low-tension Switchboard.

sures on the feeders may be read on a single voltmeter successively. The bus pressure is usually indicated by a separate voltmeter, as this pressure should be visible to the operator at all times.

The individual regulation of feeder pressure is not feasible in direct-current systems except for very long feeders which may be equipped with a booster set, or with very short

Fig. 18. Synchronous Converter Substation.

feeders which may have a resistance in series to absorb part of the pressure.

Booster sets for use on three-wire feeders commonly consist of two generators of sufficient ampere capacity to carry

the full load of the feeder and voltage range sufficient to make up for the feeder loss, usually at least 40 to 50 volts. These are driven by direct connection to a 230-volt motor of proper capacity. The booster generator fields must be designed to operate throughout the full range of pressure without trouble at the brushes, and must have independent field-rheostat control in order to permit compensation for drop on the neutral in case of unbalanced load. The location of a booster set should be such that the length of the feeder cables which are looped through the booster will be as short as circumstances will permit.

Feeder resistances are to be avoided as far as possible, and are usually not necessary on more than one or two very short feeders. Where necessary, they must be of a design which will carry the feeder current at full load without excessive temperature rise. This necessitates a special design of rheostat. Wire coils have been used for smaller feeders, but for those carrying 500 amperes and upward, strips of heavy, galvanized sheet-iron, mounted on suitable insulating supports and surrounded with a wire netting for protection, have given good results. There should be several sections so that the operator can adjust the resistance for different loads.

**Motor-generator Stations.** — Motor generators are commonly installed in sizes of 300 to 1000 K.W. These sizes are preferably wound for the transmission voltage where pressures up to 15,000 volts are used, as the extra space required for the transformers is often a considerable item in the cost of the building and real estate as well as in the cost of the equipment itself.

Synchronous motor sets are started preferably from the direct-current side in order to avoid disturbance in the transmission system. They are then synchronized and connected in parallel with the incoming line. Induction motor sets

are started by the use of resistance in the motor which gives good starting torque with a starting current little in excess of full-load current. The induction sets are started first in an emergency, thus furnishing direct current from which to start the synchronous sets. The high-tension line equipment is similar to that outlined for a transformer substation.

**Synchronous Converter Substations.** — In converter substations the electricity received from the transmission system passes through suitable oil-switching arrangements to step-down transformers which deliver a secondary pressure suitable for the rotary converter. From the transformers the current passes through a potential regulator to the collector rings of the converter and thence through its windings to the commutator from which direct current is delivered to the brushes. The direct current passes through a circuit breaker and switch to its bus bar, from which the feeders are carried to the distributing mains. Two or more direct-current bus bars are usually provided to facilitate the regulation of pressure during the period of heavy load.

The three-phase shell type of transformer, air-cooled, has been used quite generally for this class of service owing to the economy in first cost and in floor space. The air for cooling is blown through ducts within the case, and in substations of 2000 K.W. or more it is sometimes necessary to provide ducts to carry the heated air outside the building. This requires a suitable blowing outfit and space for air chambers under the transformers.

In large three-wire Edison systems it is desirable to use six-phase converters wound for the voltage across the outer wires, in order to avoid the multiplication of the number of units, and the increased expense incident thereto. The unbalance of the system may be cared for by one pair of 110-volt machines or by a motor-generator balancer set, or by

the use of six-phase diametrically connected transformer secondaries arranged as in Fig. 19. The latter plan has the advantage that no 110-volt machines are required in the substation. The neutral of the direct-current system is connected directly to the secondary neutral of the transformers and any unbalance is thus cared for. The unbalance in a large system is rarely over 5 per cent and the scheme is found very satisfactory in most instances.

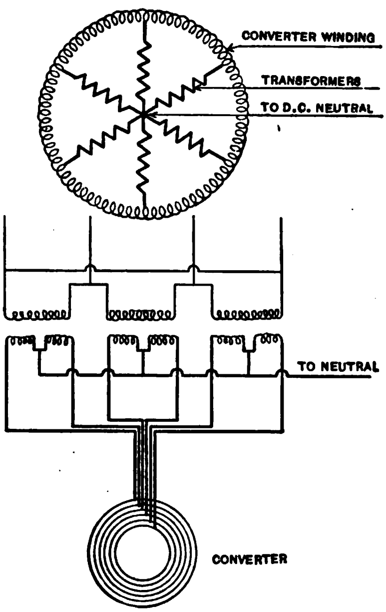


Fig. 19. Connections of Six-phase Converter.

The use of the six-phase connection and converter winding reduces the length of the path traveled by the current in passing through the armature and thus reduces the losses and the heating. Theoretical calculations based on sine waves indicate that a direct-current generator rated at 100 K.W. may be rated at 131 K.W. as a three-phase converter, or at 194 K.W. as a six-phase converter, for the same rise of temperature.

The theoretical ratio of transformation in voltage in passing from the collector rings on the alternating-current side to the direct-current brushes is as 61 to 100 in a three-phase converter and as 71 to 100 in a six-phase converter. These are based on the assumption of a sine wave of E.M.F. and may, therefore, vary somewhat in actual practice.

It is usual to protect the converter by a reverse-current

relay which opens the circuit breaker in case the flow of energy is reversed, as in the case of a breakdown in a transmission line, and shuts the machine down. Without such protection the reverse current might weaken the field of the converter and cause it to speed up quickly to a dangerous speed. The reverse-current relay does not operate below 10 per cent of full load, and a speed limit consisting of a centrifugal switch is often provided as further insurance against dangerous peripheral speeds. The speed limit is rarely called upon to act and should, therefore, be tested at regular intervals. Accidents to converters in which machines have been wrecked have occurred in nearly all large systems, and the provision of such accessories must not be overlooked where the unit operates in parallel with a direct-current system having other sources of supply.

Variation of the bus pressure by means of the field rheostat cannot be accomplished in a plain converter without affecting the power factor. An induction regulator is, therefore, commonly provided between the transformers and the collector rings of the converter. This is usually controlled by a small, worm-geared motor from the switchboard.

In recent years there has been developed a type of converter having split poles which are so designed that a considerable range of pressure regulation by means of the field rheostat is permissible without serious interference with the power factor. No regulator is required with this type of converter.

**Starting of Converters.** — The arrangement of starting devices for synchronous converters is a matter of great importance, as it must be possible to start them quickly and without serious disturbance to the system in regular operation and in emergency. The converter may be started by a supply of

current from either side or by a starting motor direct connected to the shaft. When started from the direct-current side a rheostat is used in series with the armature, as in starting a direct-current motor. The starting current, however, has two paths, one through the converter windings from brush to brush, and another through the collector rings to the transformer coils and thence back again to the converter armature. While the converter is turning slowly, the frequency of reversal of the current through the transformer coils is low and the choking effect is small. The starting current from the direct-current side is, therefore, more than that of a motor of the same size without load. When the machine has come up to speed the potential regulator is adjusted to bring the pressure of the converter up to that of the transmission system, and the rotary is synchronized with the transmission system and connected to it. The field and regulator are manipulated to bring the power factor up to unity and to adjust the load carried by the unit to the desired amount.

In case a total shutdown of the system removes the supply of direct current for starting, means must be at hand for starting from the alternating current. Converters may be started from the alternating side with the field coils open as in starting a synchronous motor, and the pressure reduced to about half normal pressure to keep the starting current within limits. This may be done by means of a starting compensator on the high-tension side of the transformer or by means of taps on the secondary winding. The latter is preferable as no autotransformer or extra high-tension switching operations are required.

In this method after the machine is brought up to speed its fields are excited and the polarity noted, as it may come up reversed. If so, the direct-current voltmeter on the machine gives a negative reading. The field connections are then

reversed by means of a switch provided for the purpose and the machine slips back one pole. As soon as it has done so the direct-current voltmeter swings to a positive reading, when the field is again reversed and the polarity remains correct. The starting switch is then thrown to the full pressure, the machine pressure is equalized and it is connected to the direct-current bus.

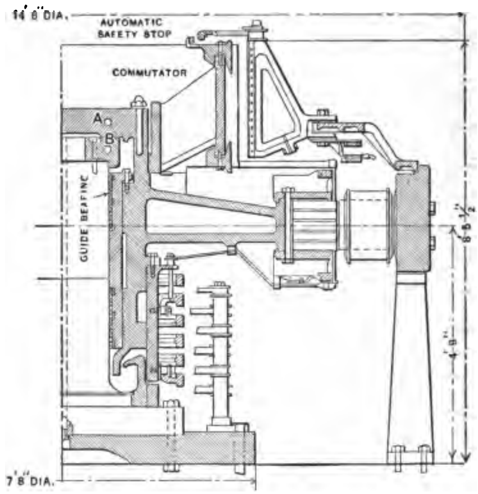



Fig. 20. Section of Vertical Converter.

The current required in starting from the alternating-current side is from 150 per cent to 200 per cent of full-load current on a 500 K.W. converter and somewhat less on larger sizes. The direct-current starting current, however, is but 25 to 30 per cent of full-load current. This small starting current makes this method preferable in cases where there are several machines or where the direct-current distributing system has sufficient capacity to furnish the starting current without serious disturbance. In such cases the normal method of starting is from the direct-current end.

Sufficient machines should be equipped for alternating-current starting in a given substation to insure a supply of direct current for starting the other units. Where sufficient storage-battery capacity is installed the direct-current supply may be relied upon at all times.

Fig. 21. Vertical Converter.

The synchronous converter has also been adapted to operation on a vertical shaft in a manner similar to the frequency changer described heretofore. This machine is, however, supported on a bearing which operates on a pedestal that passes up through the center of the machine to the top. The bearing is thus accessible from the top by the removal of a plate

instead of from below. The general arrangement is illustrated in cross-section in Fig. 20 and the external appearance in Fig. 21.

These machines have been made in units of 1000 and 2000 K.W., the first of this type having been installed in Chicago in 1907.

The interior of a converter substation is illustrated in Fig. 18.

**Storage-battery Stations.** — One of the principal advantages of the direct-current system of distribution is the possibility of the use of a storage-battery reserve. Before the use of the battery became general, it was not an uncommon thing in the larger systems to have the service seriously interrupted through accident in the generating or transmission system. With the introduction of the storage battery these interruptions were largely obviated, only serious accidents affecting the major part of the system being the cause of shutdowns. The smaller disturbances occur in a large system protected by batteries without appreciably affecting the service. The usual arrangement of battery connections is shown in Fig. 22. Taps are brought out from the end cells to a number of terminals arranged to permit the battery to be discharged at the desired voltage.

Connection is made from each end-cell terminal to a bus bar by a sliding contact which bridges the gap between the bus bar and the terminal. The voltage of each cell being about two volts, the pressure delivered by the battery to the bus bar will vary according to the position of the sliding contact. When the battery is required to discharge the sliding contacts are moved toward the outer ends, thus raising the pressure of the battery and causing it to deliver energy to the bus bar. When no energy is required from the battery the end-cell contact is set so that the battery pressure and the

bus pressure balance and the battery floats on the system. In case of a reduction in the bus pressure due to a failure in the supply of energy, the battery immediately begins to discharge to the bus, thus tending to hold the pressure up and preventing a complete interruption of service. The extent of the interference depends upon the relative capacity of the

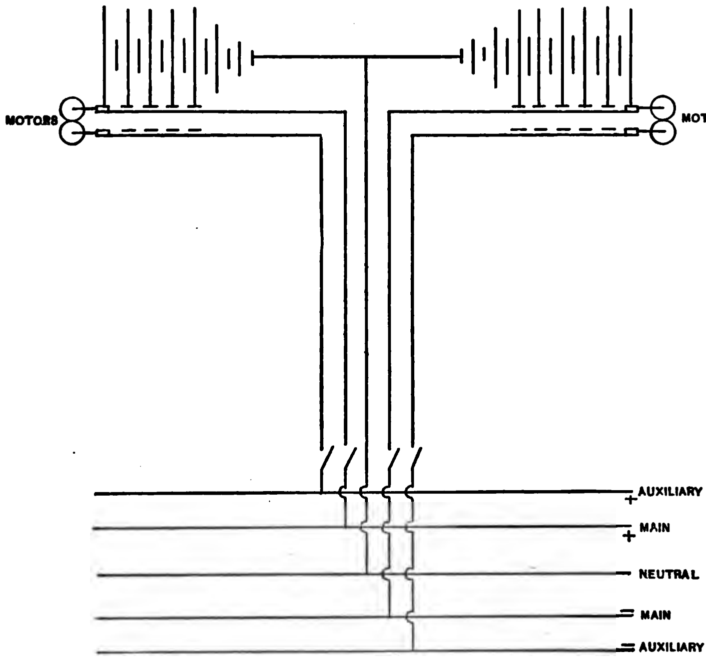



Fig. 22. Battery End-cell Connections.

battery and the load on the bus at the time. During the hours of light load the operator's adjustment of the end-cell switches is sufficient to restore the pressure to normal in a very short time, so that the consumer notices nothing beyond a slight flickering in the lights.

The maximum load in a large system is usually considerably greater than the average load, and it is not feasible to provide

sufficient battery to care for a serious accident at the hour of the maximum. The chances of the breakdown occurring at this time being rather remote and the maintenance of batteries being expensive, it is not usual to provide more than 25 to 40 per cent of the maximum load in battery capacity.

Two or three busses are provided, so that the battery may discharge simultaneously to main and auxiliary busses at different pressures if required. It is desirable to keep the battery floating on the main bus while it is being charged through another bus. The battery may be charged through a booster from the main bus, or from a separate converter or generator wound for the higher pressure required for full charging.

The battery as installed in American practice is usually arranged for motor control of the end-cell switches with indicators on the switchboard to show the operator the position of the end-cell switches on each bus, ammeters on each bus and pressure connection by which the voltage of individual cells may be taken.

The most essential points in the construction of a battery station are ample space, proper ventilation and sufficient strength to support the weight of the cells.

The cells should be set side by side so that the plates of neighboring cells can be joined together by a lead bar without the use of copper bus-bar work as far as possible. The floor space required by a battery is much more than that which is needed for an equal capacity in converting apparatus. It is sometimes necessary on this account to put parts of a battery on separate floors.

The use of sulphuric acid as an electrolyte, and the evolution of gases from the battery, tend to keep the air in a battery room heavily laden with sulphuric-acid vapor. This acid corrodes all the common metals except lead and many organic substances. It is therefore necessary to protect all

structural steel work with building tile and plaster and to keep all copper bus work well painted. As a further means of reducing the corrosive action ample ventilation must be provided. Where natural ventilation cannot be secured, fans must be provided discharging through a stack. During the

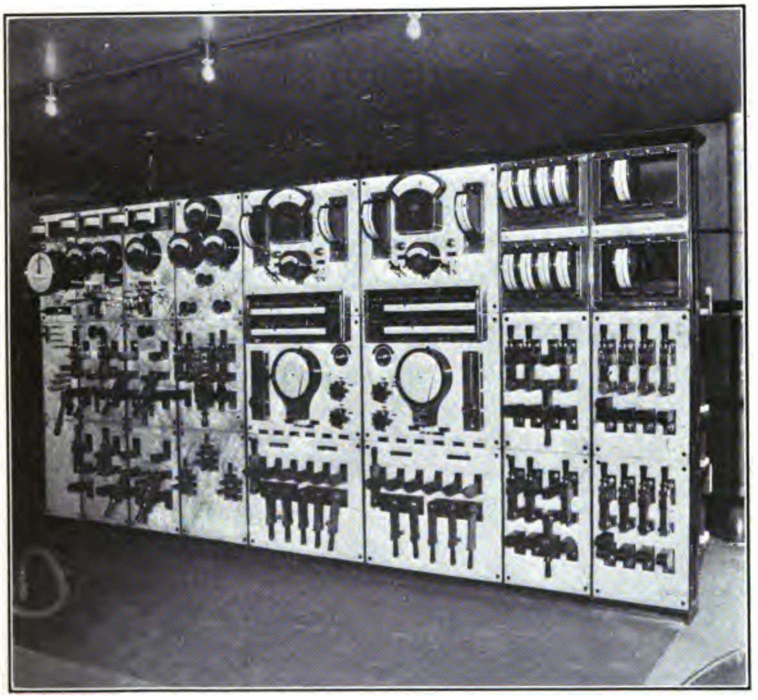


Fig. 23. Storage Battery Switchboard.

summer months open windows may be relied upon where batteries are sufficiently remote from adjoining buildings to avoid interference with the rights of others. The floor of the battery room must be arranged to drain off any leakage of the electrolyte. The use of cement floors is not permissible on account of the action of the acid. It is therefore usual to

lay a floor consisting of a layer of roofing paper well coated with compound and over this a floor of vitrified tile brick with the spaces between the bricks carefully filled with compound. Such a floor will not permit the leakage of any electrolyte to the lower floors, and is not affected materially by the acid.

The operation of the battery being affected by the specific gravity of the electrolyte, it is necessary to have a supply of pure water for the purpose of diluting the acid at intervals. The provision of facilities for the storage or manufacture of distilled water is therefore usually necessary.

The end-cell connections are preferably terminated on an end-cell switch built into one wall of the battery room and facing toward the outside. This keeps the strong acid fumes away from the end-cell switch and other substation apparatus. A battery switchboard with end-cell indicators and controlling devices is illustrated in Fig. 23.

# CHAPTER III.

## VOLTAGE REGULATION.

THE inherent sensitiveness of the incandescent lamp to variations in pressure necessitates refinements of regulation in electric lighting work which are not required in purely power or traction enterprises. The excellence of a central station's lighting service is determined very largely by the attention given to pressure regulation, and much thought has therefore been given to this subject by engineers from the earliest days of the industry.

In general, the regulation of pressure is accomplished by variations of bus voltage and by control of the pressure on individual feeders.

**Low-tension Networks.** — In low-tension networks, which are generally operated with direct current, uniform pressure is maintained on the mains by varying the bus pressure as the load changes and by the fact that the regulation of pressure is to some extent automatic. When a heavy load is placed at any point on a network the pressure near that point is lowered somewhat, causing current to flow from all adjacent feeders toward the low point in proportion to the capacity of the mains in the vicinity of the load. The heavy load is thus carried in part by each of the feeders nearest the low point, which tends to support the pressure in that locality. When the adjacent feeders take the added load the pressure at their ends is held by raising the bus pressure, and the system tends thus to automatically equalize the pressure within certain limits.

The different lengths and sizes of the feeders tend, however, to produce higher pressure on the network near the station and lower pressure at remote points during the heavy-load period. In the earlier development of networks it was customary to insert resistances in the feeders to keep the pressure down on the short feeders and to afford means of shifting load from one feeder to another. This practice was discontinued as a general thing because of the inherent tendency of the network to regulate the pressure automatically. The loss of energy in feeder resistances was a considerable item and the space required is considerable where feeder loads are heavy. They are used in modern practice only for very short feeders, where regulation cannot be secured without them.

It is found desirable to provide two or more separate busses and to arrange the switchboard so that the shorter feeders can be carried on one at a lower pressure and the longer feeders on the other busses at higher pressures. Each bus is supplied from a source which can be independently regulated, and each zone may therefore be carried at a pressure suited to average drop on its feeders.

This arrangement necessarily requires a sufficient number of sources of supply of the proper capacity to carry the loads on the several busses, and is therefore only applicable to stations and substations having several units.

The operation of several busses is necessary only during the hours of heavy load since the difference between the drop on the longer and shorter feeders is not so great during the hours of light load, and all feeders can be carried from one bus.

It is often practicable to prevent pressure from running too high during the light-load period by opening a part of the feeders running to a district, transferring the load to the remaining feeders and increasing the drop on them.

With very long feeders it is sometimes necessary to install

a motor-driven booster in series with the feeders to hold the pressure up. Such boosters may be compounded to automatically maintain constant pressure at the feeder end as the load changes. Where storage batteries equipped with end-cell switches are available, it is sometimes feasible to put the longer feeders on the battery through a separate bus and thus avoid the use of a booster. The installation of a booster is not justified until the fixed charges on the cost of the feeder capacity required to produce equivalent results exceed the fixed charges on cost of the booster equipment plus the value of the loss due to its operation.

It is usual in low-tension networks to run pressure wires from the principal feeder ends back to the station where they are connected to a multiple-point switch in such a way that a voltmeter may be connected to the pressure wires of any feeder, and the pressure at any point in the network may thus readily be known at any time.

In operating the system a feeder which represents the average condition in any zone is selected as a standard feeder. The pressure wires of this feeder are run to a separate voltmeter which is used for regulating the bus which supplies the zone. The operator manipulates the field rheostat of the machines which are carrying the load as may be necessary to hold the pressure as indicated by the voltmeter on the standard feeder constant. A similar standard feeder is required for each bus, and in large systems a second standard is often maintained for use in case of emergency.

In stations where a storage battery auxiliary is provided, it is usual to adjust the battery pressure to that of the bus and connect them in parallel. This permits the battery to float on the bus and thus automatically charge and discharge as the pressure rises above or falls below the normal. The effect of this is to steady the bus pressure greatly and to partially sustain it in case of interruption of the power supply.

**Alternating-current Networks.** — In alternating-current systems the problem of pressure regulation is solved in quite a different way. Individual feeder regulators which waste but little energy permit the economical operation of most of the feeders on one bus if it is desired, though two busses are usually provided for other reasons. In low-tension networks the conditions are very similar to those found in a direct-current network, but the problem is much more easily met because of the availability of feeder regulators. When a feeder becomes overloaded the regulators of adjacent feeders may be used to raise these feeder end-pressures and thus cause these feeders to take part of the load of the overloaded feeders. Where the feeders are low tension as well as the mains, and are installed underground, pressure wires may be embodied in the feeder cables, as is customary in direct-current distribution, at a small expense. If the lines are overhead or the construction is such that separately insulated pressure wires are required, it is usually less expensive to utilize line-drop compensators instead.

**Primary Systems.** — In areas in which the load is so scattered that the distribution is effected chiefly by means of primary mains, it is usually found desirable not to interconnect adjacent feeders. This requires that each feeder be independently regulated to deliver the proper pressure at its terminus, and feeder regulators are therefore very essential to a system having a number of feeders of different lengths and sizes.

**Feeder Regulators.** —The design of an efficient and practical form of feeder regulator is fortunately quite feasible, and there are two types in general use in America. Stillwell, at an early date, devised a transformer with a secondary winding tapped at intervals, the taps being brought out to a dial switch. By the

motion of this dial switch handle, more or less of the secondary windings could be thrown in series with the feeder, thus raising or lowering the pressure. A reversing switch was also provided by which the pressure of the regulating transformer could be op-

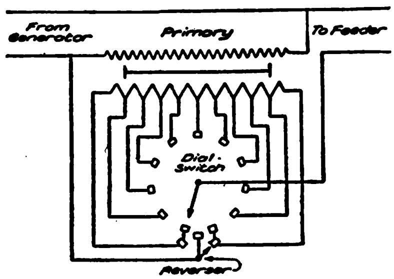



Fig. 24. Transformer-type Regulator Connections.

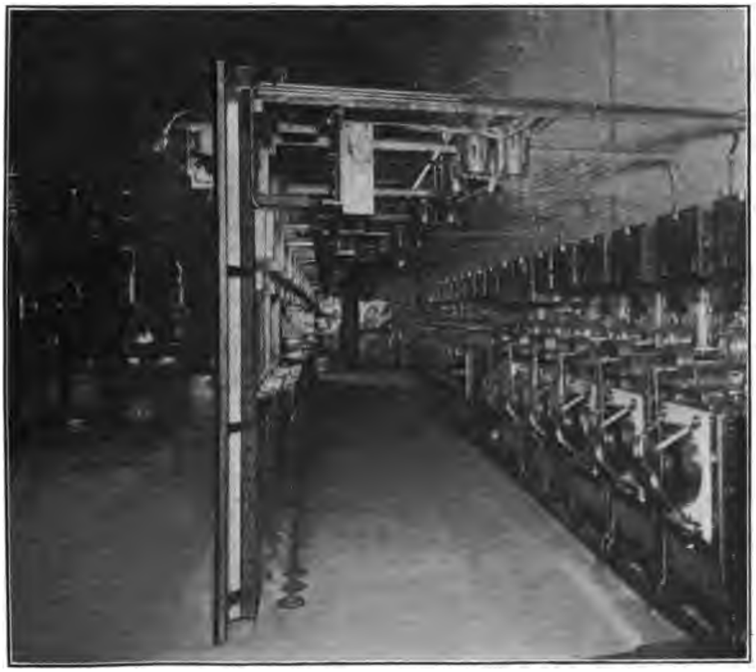


Fig. 25. Transformer-type Regulators.

posed to the bus pressure if desired. This type is illustrated in Figs. 24 and 25.

Another type of regulator which was developed somewhat later is known as the " induction " type.

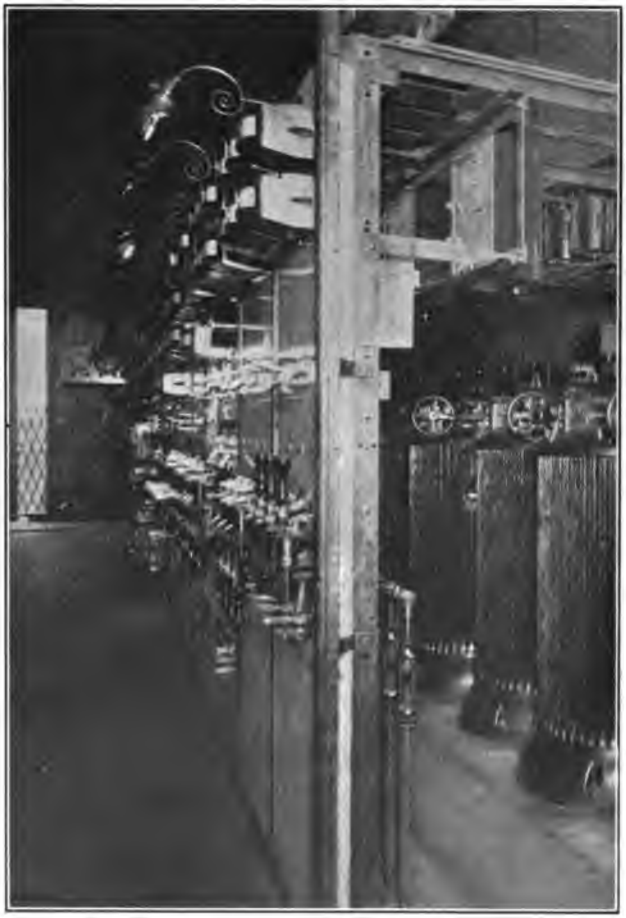


Fig. 26. Induction-type Regulators.

In this regulator the variable voltage of the secondary is secured by turning the movable core on which the secondary is wound to different positions, thus linking more or less of

the magnetic flux. If turned more than 180 degrees the secondary voltage is reversible through its full range.

This type is inferior in efficiency and power factor to the Stillwell type, owing to the presence of an air gap in the magnetic circuit, but its freedom from sliding contacts renders it more suitable for use in cases where remote or automatic control is employed. Fig. 26 illustrates a typical equipment of this class, connections for which are shown in Fig. 27. An induction regulator is actuated by a small three-phase motor mounted on the regulator frame. A reversing switch which is

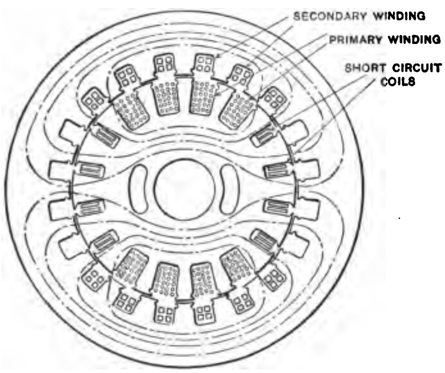



Fig. 27. Section of Induction Regulator.

usually located on the feeder panel enables the operator to move the regulator in either direction, thus raising or lowering the pressure. A limit switch is provided for the purpose of cutting the motor out when the regulator has been brought around to the position of the maximum boost or choke. Hand control is also provided for use in emergency.

**Automatic Regulation.** Automatic feeder regulation has been adopted quite generally in recent years in conjunction with the use of motor-operated regulators. In the earlier forms, power was supplied by a motor-driven line shaft to

which the regulators were belted. Direct-current magnetic clutches were arranged to engage the dial switch of the regulator and so raise or lower the pressure, as necessary, to hold it constant at the feeder end.

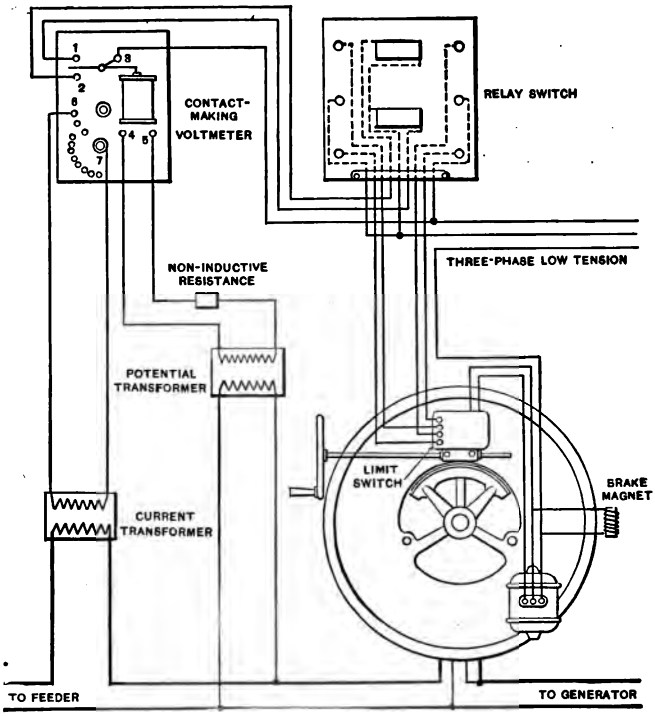



Fig. 28. Connections of Automatic Induction Regulator.

The adaptability of this arrangement was limited by the use of direct current, which is often not available in alternating-current stations. The use of a line shaft was also impossible in many places, and the individual motor drive has superseded the earlier forms.

The arrangement shown in Fig. 28 is one form of automatic motor-controlled regulating apparatus. The device called a

contact-making voltmeter consists of a solenoid containing a plunger which is actuated by an adjustable series winding in opposition to a potential winding. A change in the volume of current passing over the feeder causes the plunger to move and closes one of the voltmeter contacts. This operates the relay switch, which in turn starts the motor, moves the regulator and raises or lowers the feeder pressure.

The series coil is made adjustable to permit its adaptation to feeders of various sizes and lengths, as more fully described later in this chapter.

In practice the maintenance of relay contacts has been found somewhat troublesome, but where motor-controlled regulators are used the addition of the devices necessary to adapt them for automatic operation is comparatively inexpensive and is amply justified by the superior results secured in pressure regulation.

**Bus-bar Regulation.** — The automatic regulation of bus pressure is desirable where automatic feeder regulation is not used, as the operator can properly care for gradual changes in the feeder load by hand regulation, if the bus pressure is held steady by the automatic devices.

The automatic regulator devised by Tirrill has proved very successful in the control of bus pressures. The general scheme of connections for this device is illustrated in Fig. 29, and the action may be described thus: —

The secondary circuits of the potential and current transformers of the generator are led through a solenoid in a compounding relation. The current section is subdivided so that different rates of compounding may be secured. A movable plunger is actuated by this solenoid, which in turn actuates a counterweighted lever, the opposite end of which is equipped to make electrical contact in a relay circuit. The other contact terminal of this relay circuit is carried on a similar lever

which is actuated by the plunger of a direct-current solenoid. This solenoid receives current in proportion to the pressure at the exciter terminals. The relation of these contact-making levers is such that increased pressure at the exciter brushes tends to open the relay circuit, while increased pressure at the main-generator terminals tends to close this relay circuit. The closing of the relay circuit demagnetizes the relay as the other arm of the relay is continuously excited in the opposite sense. As soon as the poles of the relay are

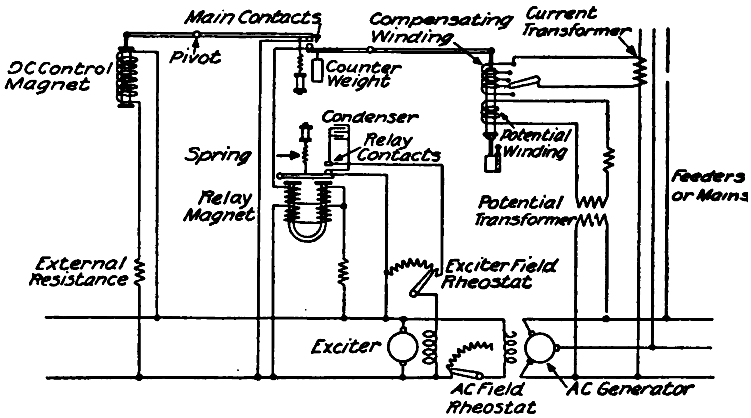



Fig. 29. Tirrill Regulator Connections.

demagnetized its armature is withdrawn by a spring. This closes a circuit which shunts the field rheostat of the exciter and greatly increases the terminal pressure at the exciter brushes. This increases the pull of the direct-current solenoid plunger and opens the relay circuit, thus weakening its pull. The result is a rapid vibratory action which is kept up continuously at a constant rate while the load remains constant. As the load increases the current winding on the alternating-current solenoid exerts an increased pull on the plunger which causes the lower contact of the relay circuit to

move upward toward the other contact and thus close the relay circuit sooner. This raises the exciter pressure, and thereby the generator pressure, until it has been restored to normal. The vibratory action continues as before but the contacts are working in a slightly higher position in space, thus forming a "floating contact."

A condenser is used to diminish the action of the arc at the contact which shunts the exciter rheostat.

The ability of the shunt contacts to break the circuit is the limiting feature of the apparatus. This limit is reached at about 50 K.W. on the exciter or 2000 K.W. on the generator. Above this two or more breaks must be used in series, each shunting a portion of the exciter field rheostat.

Where there are several units in parallel in a station the regulator may be applied to the exciter for a part of them and the bus regulated for constant pressure, with the series coil of the alternating solenoid cut out. With this arrangement the bus pressure may be maintained constant at any desired point by the insertion of an adjustable resistance in the pressure circuit of the alternating solenoid.

**Line-drop Compensators.** — The feasibility of having at the station an accurate indication of the pressure at each feeder end, without the use of pressure wires, has made the line-drop compensator an invaluable adjunct of alternating-current systems. The function of the line-drop compensator is to introduce into the feeder voltmeter circuit a counter E.M.F. which reduces the reading of the voltmeter by an amount equivalent to the line drop, and therefore indicates to the station operator the pressure delivered at the feeder end. The compensator circuit is a miniature of the feeder itself, the pressure transformer representing the bus bar, the compensator the line, and the voltmeter the load. Since the feeder has both resistance and inductance the compensator has two sec-

tions representing noninductive and inductive drops. These sections are subdivided into a number of parts, representing 1, 3 or 5 per cent each, and equipped with dial switches so that they can be adjusted to correspond with the drop in any feeder having a full-load drop up to 25 or 30 per cent. The counter E.M.F. is produced by passing current from the secondary of the feeder current transformer through the two sections of the compensator in series.

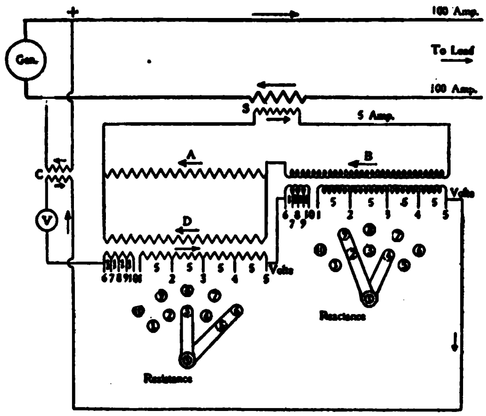



Fig. 30. Connections of Westinghouse Line Drop Compensator.

The inductive as well as noninductive drop being compensated for by the apparatus, the indications of the voltmeter are correct at all loads and at any power factor.

The details of the compensator have been worked out differently by two manufacturers in America. The apparatus as perfected by the originators of the device, the Westinghouse Electric Manufacturing Company, is illustrated diagrammatically in Fig. 30.

This company provides compensators for a maximum drop of 6, 12, 24 or 36 volts, the one illustrated in Fig. 30 being a 24-volt compensator.

The current from the secondary of the current transformer $S$ passes through the inductive section $B$ and the noninductive section $A$ in proportion to the load on the feeder. The ratio of the current transformer must be such that at its full-rated load the current in the secondary will not exceed 5 amperes. The inductive section is wound on an iron core which serves also as the core of a pressure transformer.

The secondary winding is divided into four sections of five volts each, and four of one volt each. The five-volt terminals are connected to the contacts numbered 1, 2, 3, 4 and 5, and the one-volt terminals to the contacts numbered 6, 7, 8, 9 and 10. The arms may be independently adjusted, thus permitting any setting from 1 to 24 to be made, as in the following table:

| Switch points. | Per cent compensation. | Switch points. | Per cent compensation. |
|---|---|---|---|
| 5–6 | 0 | 3–9 | 13 |
| 5–7 | 1 | 3–10 | 14 |
| 5–8 | 2 | 2–6 | 15 |
| 5–9 | 3 | 2–7 | 16 |
| 5–10 | 4 | 2–8 | 17 |
| 4–6 | 5 | 2–9 | 18 |
| 4–7 | 6 | 2–10 | 19 |
| 4–8 | 7 | 1–6 | 20 |
| 4–9 | 8 | 1–7 | 21 |
| 4–10 | 9 | 1–8 | 22 |
| 3–6 | 10 | 1–9 | 23 |
| 3–7 | 11 | 1–10 | 24 |
| 3–8 | 12 | ........... | ........... |

The noninductive section is similarly equipped and the settings are made in the same way.

The pressure from the main pressure transformer $C$ passes through the feeder voltmeter to terminal 6, through the two movable arms to 3, through the portion of the noninductive section, which is included between 3 and 5, thence through the inductive section by a similar path through the portions

between 9 and 6, and between 4 and 5. It then returns to the pressure transformer. In making this circuit the impressed pressure has been opposed by a counter E.M.F. of 10 volts in the noninductive section and by 8 volts in the inductive section.

The reading of the voltmeter is therefore reduced by the same amount as would be a voltmeter connected at the end

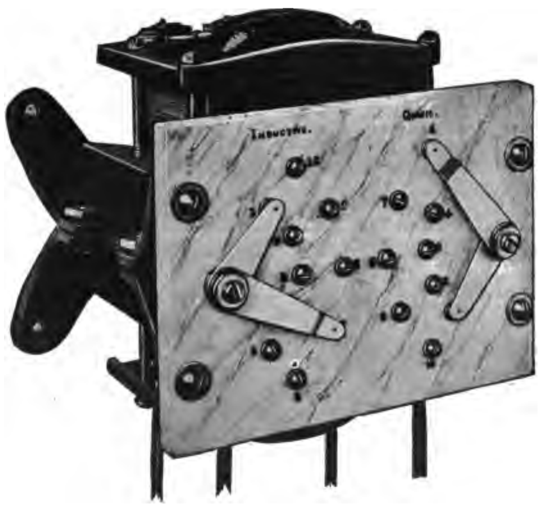


Fig. 31. Westinghouse Line Drop Compensator.

of a feeder having a resistance drop of 10 volts (secondary) and a reactance drop of 8 volts at full load. If the normal secondary pressure delivered to the feeder voltmeter is approximately 100, these drops are also percentages of the secondary pressure, but if the secondary pressure on the voltmeter is 110 or any other appreciably different voltage, the compensator figures cannot be considered as percentages of the secondary pressure.

The general external appearance of this type of compensator is illustrated in Fig. 31.

The compensator, as worked out by the General Electric Company, is somewhat simpler in construction. The general scheme of connections is illustrated in Fig. 32.

In this type the current from the main current transformer at maximum load is reduced from 5 amperes to 1 ampere by a current transformer inside the case of the compensator.

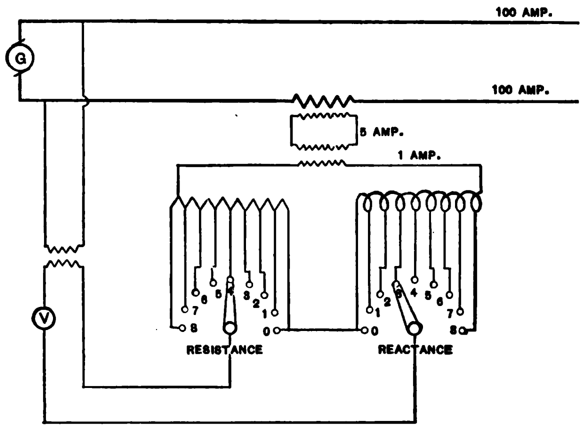



Fig. 32. General Electric Compensator Connections.

There is but one movable arm on each section and 8 points each of which represents 3 volts when 1 ampere is flowing in the compensator.

The compensator in Fig. 32 is set so as to introduce in the voltmeter circuit an inductive counter E.M.F. of 9 volts and a noninductive counter E.M.F. of 12 volts when the feeder is carrying full load.

The points being numbered, the operation of setting is easily accomplished by any station attendant without danger

or confusion or reference to a table of settings, corresponding to various percentages of compensation. The general appearance of this type is shown in Fig. 33.

Fig. 33. General Electric Line Drop Compensator.

**Calculation of Compensator Settings.** — With a feeder of No. 0 wire, 5000 feet long, single-phase, overhead wires 12 inches apart, pressure 2200 volts at feeder end, frequency 60 cycles, current transformer rated 100 to 5 amperes, pressure transformer rated 2200 to 110 volts, how should the compensator be set?

The full-load rating of the compensator being 5 amperes that of the feeder is 100 amperes. The ohmic drop on a No. 0 feeder at 100 amperes is .2 volt per ampere per 100 feet of two-wire circuit. Hence the ohmic drop is $100 \times 5 \times .2 = 100$ volts, or 4.5 per cent. Likewise the inductive drop is .22 volt per ampere per 1000 feet, and the inductive drop on the feeder $100 \times 5 \times .22 = 110$ volts, or 5 per cent.

These values may be found for various sizes of wire in Table 21, Chapter XV.

If the primary mains are designed to give not over 2 per cent ohmic drop, the transformers 2.0 per cent and secondary mains 2 per cent, the average ohmic drop from the feeder end to the consumer's premises should be about 3 per cent. The inductive drop should be about 3 per cent also. Assuming that these averages are applicable to the major portion of the distributing mains, they may be added to the drop on the feeder and the compensator set so that the drop on both feeder and distributing system will be taken into account. The pressure may thus be regulated to give constant pressure at the average consumer's premises. In this case the total ohmic drop is $4.5 + 3 = 7.5$ per cent, while the inductive drop is $5 + 3 = 8$ per cent.

If a Westinghouse 24 per cent compensator were used, the setting of the resistance section would be $7\frac{1}{2}$ per cent of 110, or 8 volts, and of the reactance section 8 per cent of 110, or 9 volts. The resistance arm would therefore be set at 4–9 and the reactance section 4–10. The operator will then keep the feeder voltmeter at 110 volts at all loads, this being maintained as a standard pressure.

With a General Electric compensator having 8 points on each part, the points have a value of 3 volts each, and the setting must be made on the nearest point. In this case the arm of each section would therefore be set at the third point.

On a two-phase four-wire feeder the method of connection is similar to that used in the single-phase feeder, except that one equipment is required for each phase. The method of calculating the setting for each phase is the same as in the case of a single-phase feeder. With a three-wire two-phase feeder, which always carries a balanced load, a compensator is required in the two-phase wires only. But with unbalanced

load one is required in each of the three wires. The connections should be as shown in Fig. 34, when the load is unbalanced.

In calculating settings it must be borne in mind that the values of resistance and inductance per 1000 feet used in the case of a single-phase feeder are based on two wires, whereas in a three-wire feeder each compensator corrects the drop in one wire only. The values used for single-phase feeder resistance must therefore be divided by two before

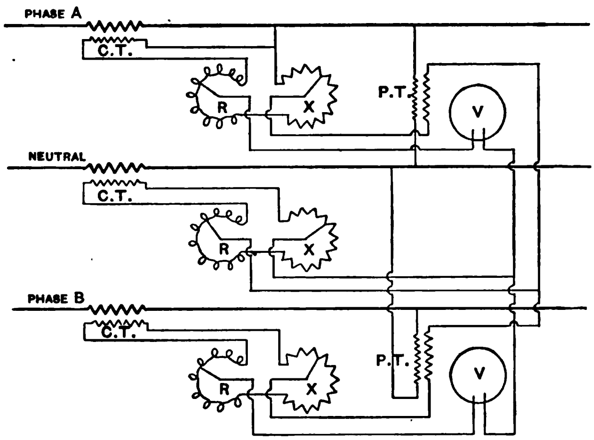



Fig. 34. Compensator Connections, Two-phase Three-wire Circuit.

being applied to a three-wire feeder whether two-phase or three-phase.

In case the common wire is equipped with a current transformer having a higher ratio than the other wires, this must be taken into account. Likewise if the common wire is larger than the other wires, the proper values must be used for this conductor. The allowance made for drop in the primary mains, transformers, secondaries, etc., should be added to the calculation for the phase wires of the feeder only as it is in phase with the drop in these wires.

With a two-phase feeder of three No. 0 wires similar in other respects to the single-phase feeder previously described, and with a current transformer in the middle wire rated at 150 to 5 amperes, the ohmic drop in the middle wire would be $5 \times 150 \times .1 = 75$ volts, or 3.5 per cent, and the inductive drop would be $5 \times 150 \times .11 = 82$ volts, or 4 per cent. The drop in the outer wires would be $5 \times 100 \times .1 = 50$ ohmic and 55 inductive, or about 2.5 per cent. Adding the allowance of 3 per cent for drop in the distributing mains, the compensator on the outer or phase wire should be set at 6 per cent on each dial of the compensator. The compensator on the middle wire should be set at 4 per cent on each dial.

In the case of a three-wire three-phase feeder carrying unbalanced load, a compensator is required in each wire. For instance, if the feeder previously used for illustration were a three-wire three-phase feeder, the ohmic drop in each wire will be $5 \times 100 \times .1 = 50$ volts, and the inductive drop 55 volts. These values are respectively 2.2 and 2.5 per cent of the working pressure 2200 volts. In this case the drop on each wire affects the pressure on two of the three phases. The compensators must therefore each interpose a counter E.M.F. in the voltmeter circuits in proportion to the drop in the phase wire which it represents. This drop must be expressed as a percentage of the working pressure.

The diagram of compensator connections for this system is illustrated in Fig. 35.

The allowance for drop in distributing mains must be divided between any two compensators, as it is in phase with the working pressure. 1.5 per cent should therefore be added to the 2.2 per cent ohmic and 2.5 per cent inductive drops, making the ohmic setting 3.7 per cent and that of the inductive 4 per cent.

In a three-phase four-wire system operating at 2200 volts between each phase and the neutral, the method of calcu-

lating the drop is as follows: With a feeder of four No. 0 wires running 5000 feet from the station as a three-phase feeder, the drop in each wire is 50 volts ohmic and 55 volts inductive. The working pressure being 2200, this is 2.5 per cent. If the entire load of the feeder is delivered from this center of distribution the compensator on each phase wire should be set at $2.5 + 3.0 = 5.5$, or say 6 per cent on each

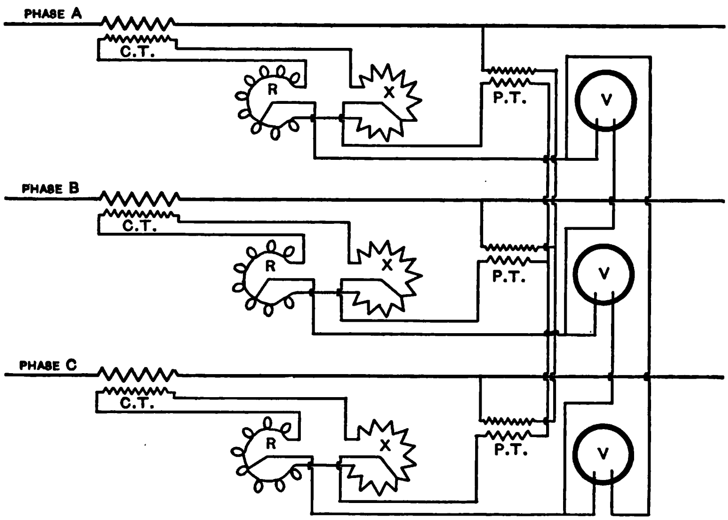



Fig. 35. Compensator Connections, Three-phase Three-wire Circuit.

dial. That on the neutral should be set at 2 per cent on each dial. If, however, the A-phase branches off with a neutral to a single-phase center of distribution 2000 feet beyond, there must be added to the A-phase setting $100 \times 2 \times .2 = 40$ volts = 2 per cent, making it 8 per cent on each branch, If the other phases branch to similar centers of distribution, at different distances, the drops must be figured as if they were single-phase feeders from the end of the three-phase transmission to the single-phase center of distribution. These

drops must then be added to the three-phase drop above calculated. On four-wire 2300–4000-volt feeders which reach the limit of three-phase transmission within 3000 feet of the

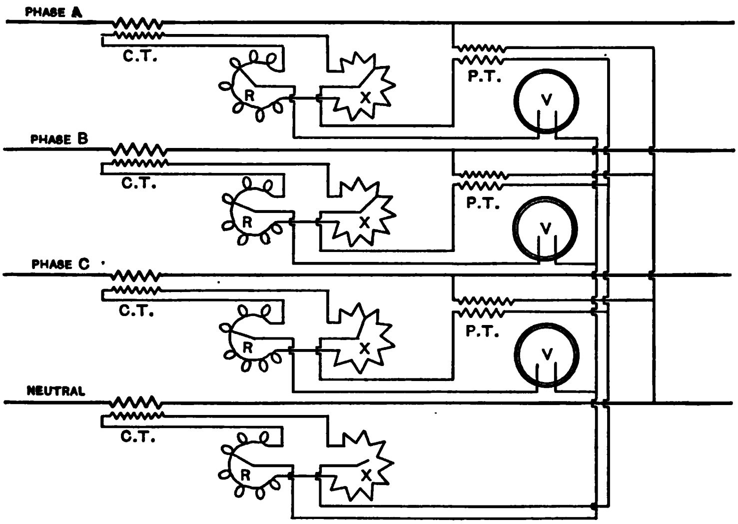



Fig. 36. Compensator Connections, Three-phase Four-wire Circuit.

station, it is usually unnecessary to install a compensator on the neutral wires, as the neutral drop is negligible, with even a considerably unbalanced load.

The connections of compensators for a four-wire three-phase feeder are shown in Fig. 36.

## CHAPTER IV.

### LINE TRANSFORMERS.

THE transformer is perhaps, next to the generator, the most important piece of apparatus which the electrical engineer has at his disposal. Without it the development of alternating-current transmission and distribution systems would have been so greatly restricted that the use of electricity could never have reached the proportions of the present. Distribution would have been limited to lower voltages and transmission would not have passed beyond the limits within which generator and motor voltages are confined, say 15,000 to 20,000 volts.

The transformer is the simplest piece of apparatus which is employed in electrical engineering. With no moving parts it is a mere combination of copper and iron which needs but the application of an electromotive force at its terminals to make it instantly operative.

The physical phenomena which take place in the transformer are, however, not as simple as its construction.

When pressure is applied to the terminals of the primary winding with the secondary circuit open, the current which flows is known as the leakage current. The leakage current is made up of two components, known as the magnetizing component and the iron loss component. The magnetizing component is that portion of the leakage current which induces a magnetic field in the iron core. The iron loss component is that portion which supplies the energy losses in the iron core.

The magnetizing component is a quarter cycle behind the

impressed voltage wave, while the loss component is in phase with it. The leakage current $L$ is therefore $\sqrt{M^2 + I^2}$, in which $I$ is the iron loss component and $M$ is the magnetizing component. $M$ is about twice as great as $I$ in distribution transformers of 2 to 50 K.W. capacity. The leakage current is readily determined from ammeter readings, while the iron loss may be found by the use of a suitable wattmeter. From these the magnetizing component may be readily calculated from $M = \sqrt{L^2 - I^2}$.

The secondary voltage is a quarter cycle behind the wave of core magnetism, which brings it a half wave behind the primary impressed pressure, or in opposition to it. The ratio of the primary to the secondary voltage is called the ratio of transformation.

When current is permitted to flow in the secondary circuit, the magnetomotive force set up in the core causes current to flow in the primary of such strength that its magnetomotive force is equal to that set up by the secondary current. For instance with 100 amperes in a secondary having 100 turns, the magnetomotive force is 10,000 ampere turns. If the primary has 2000 turns the primary current will be such as to cause 10,000 ampere turns in it. The primary current will therefore be 5 amperes plus the leakage current when the secondary is delivering 100 amperes.

**Ratio of Transformation.** — The ratio of transformation of a transformer is fixed by the ratio of the number of turns in the primary to the number in the secondary. That is, a transformer receiving energy at 2000 volts and delivering it at 200 has ten times as many turns in series in its primary coils as there are in series in its secondary coil. When a transformer is wound with two or more sections in its primary or secondary coils, its ratio of transformation can be changed by changing the connections from series to parallel. For

instance, in a 1100–2200 to 110–220 volt transformer, there are four possible combinations of connections, viz. (a) primary and secondary sections both in parallel 1100 to 110 or 10 to 1, (b) primary in parallel, secondary in series 1100 to 220 or 5 to 1, (c) primary in series, secondary in multiple 2200 to 110 or 20 to 1 and (d) primary in series, secondary in series 2200 to 220 or 10 to 1.

It is usual to make the primary winding of line transformers interchangeable so that they can be used on either 1100 or 2200 volt systems. The secondary windings of line transformers are divided so that they can be used in three-wire distribution in sizes above one kilowatt.

Transformers designed for transmission service are frequently made with several coils on both primary and secondary to permit their being connected in series for use on higher voltages later as the system develops.

The ratio of transformation is also sometimes made adjustable by steps of 5, 10 or 15 per cent, by bringing taps out from one of the windings of the transformer by which the pressure may be raised or lowered as conditions may require. Such taps are often specified in ordering transformers which are to be used with delta connection on a three-phase transmission where it is expected to raise the transmission voltage later by a change to star connection.

The ratio of transformation expressed in terms of the ratio of the number of turns in the coils is strictly true only when the transformer is carrying no load. The resistance and inductance of the windings cause a reduction in pressure of 2 to 3 per cent when the transformer is carrying full load, thus modifying the ratio of transformation slightly.

**Leakage Current.** — The ratio of the number of turns in primary and secondary being fixed by the voltages of supply and delivery, it is necessary for the designer to fix the number

of turns in one of the coils arbitrarily. This number must be high enough to furnish the magnetizing force for the core without requiring too much leakage current. This leakage current in line transformers should not exceed 3 per cent of normal full-load current except in the smallest sizes, as there are many of them on a distributing system. The combined leakage current in a large system, having a power factor of 50 to 60 per cent, tends to interfere with the regulation of the generator pressure, and to increase the energy required for excitation of the fields during the hours of light load.

On the other hand an increase in the number of turns requires a greater length of wire, which in turn tends to increase the cost of the transformer and reduce its efficiency. The number of turns must therefore be selected so that the leakage current and length of wire will be within proper limits.

**Calculation of Windings.** — The fundamental formula by which the induced voltage of a transformer is calculated illustrates these facts. The induced voltage of a transformer is $E = \frac{4.44\, fnF}{100,000,000}$, in which $f$ is the frequency in cycles per second, $n$ the number of turns in series in the coil and $F$ the total magnetic flux in the core, at the maximum point of the wave. For 60 cycles and 2080 volts this becomes

$$2080 = \frac{4.44 \times 60 \times nF}{100,000,000}, \quad \text{or} \quad nF = 781,000,000.$$

It is apparent that either the number of turns must be assumed to find the total flux, or the flux may be assumed to find the number of turns. The number of turns fixes the weight of copper and the copper loss, while the magnetic flux fixes the weight of iron and the iron loss.

It may seem at first sight that the area of the cross-section of the iron core would be about the same for all transformers designed for a given voltage without regard to size, since the product of the turns and the flux is a constant which is fixed by the voltage.

However, the exciting current may be made proportional to the kilowatt capacity and this permits the number of turns to be reduced in the larger units, thus increasing the amount of iron in the core. For instance, in a 2-K.W. transformer designed for 2080 volts there would be required about 1900 turns in the primary to keep the exciting current down to a proper amount. The total flux would therefore be $F = 781,000,000/1900 = 411,000$ lines. In a 20-K.W. unit, the full-load current being ten times greater, the exciting current may be several times greater. Assuming that the primary has 600 turns, the total flux will be $781,000,000/600 = 1,300,000$ lines. The average length of a turn is increased because of the greater area of the cross-section, and the length of wire is therefore not reduced in proportion to the reduction in the number of turns. A number of trial calculations must be made with different ratios of turns to flux until the most economical combination is found for each size.

The total magnetic flux being determined the area of the cross-section of the magnetic circuit is fixed by an arbitrary assumption of magnetic density per square inch. This value is somewhat elastic and may be adjusted within 15 or 20 per cent of a mean value in order to produce consistent designs.

**Iron Loss.** — The iron loss varies as the 1.6 power of the magnetic density. The law governing this was discovered by Steinmetz and is

$$\text{Iron loss} = \frac{KfVB^{1.6}}{10,000,000},$$

in which $f$ is the frequency, $V$ the volume of the iron, $B$ the number of lines per unit of area and $K$ a constant depending on the kind of iron used.

It is evident from this formula that if the density is increased the core loss increases more rapidly and excessive heating is likely to result. On the other hand if the density is greatly decreased the weight of iron is increased and the cost goes up.

In the smaller sizes of 60-cycle transformers, where the weight of iron is small in proportion to the copper, the density is made lower so as to partly equalize this disparity. The iron in units of 1 to 5 K.W. is therefore operated at from 40,000 to 45,000 lines per square inch. In the larger sizes it is made 45,000 to 50,000, and in transmission units as high as 60,000 lines per square inch.

At 25 cycles the total flux for a given voltage must be greater and this tends to require greater cross-section. The iron loss, however, falls off with the frequency, and the density may be increased enough to make up for the decrease in loss at the low frequency. This permits the design of 25-cycle units at densities of 60,000 to 90,000 lines per square inch. On the other hand 125-cycle units are usually operated at 30,000 to 40,000 lines. The density having been assumed, the area of the core is $A = \frac{F}{B}$, or $\frac{1,300,000}{50,000} = 26$ square inches in a 20-K.W. unit.

**Magnetizing Current.** — The magnetizing component of the leakage current for a given design may be computed from the formula $C = \frac{BL}{4.44\,NP}$, in which $B$ is the number of lines of force per square inch, $L$ the length of the magnetic circuit in inches, $N$ the number of turns and $P$ the permeability of the iron. Assuming a magnetic density of 50,000 lines per

square inch and a permeability of 2000, the magnetizing component of the leakage current would be

$$C = \frac{50{,}000 \times L}{4.44 \times 2000 \times N} = \frac{5.63\,L}{N}$$

or assuming the magnetizing current, the number of turns is

$$N = \frac{5.63\,L}{C}.$$

The number of primary turns and total flux of various sizes of 2200-volt distribution transformers are approximately as given in the following table: —

| K.W. Cap. | 1 | 2 | 3 | 5 | 7.5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mega lines .... | .26 | .411 | .550 | .700 | .88 | 1.02 | 1.2 | 1.35 | 1.45 | 1.53 | 1.7 | 1.85 |
| Turns ........ | 3000 | 1900 | 1420 | 1100 | 890 | 780 | 650 | 580 | 550 | 510 | 460 | 420 |
| Area of core .. | 6.5 | 9.5 | 12.2 | 15.5 | 17.6 | 21 | 23.5 | 26 | 27 | 28 | 31 | 34 |

The formula $E = \frac{4.44\,nfF}{100{,}000{,}000}$ has been applied numerically in the foregoing only to units designed for 2080 volts and 60 cycles. It is apparent that for higher voltages the product $nF$ will be proportionately higher and that more iron and copper will be required to construct a transformer of given capacity as the voltage is increased. Likewise if the frequency is lower the product $nF$ is proportionately higher and more copper and iron is required to construct a transformer of given type and size in direct proportion. On this account 25-cycle transformers and induction motors require more material than the similar types of 60-cycle apparatus and cost more to build.

**Types of Core.** — There are two general types of arrangement of the windings and core of a transformer. One is known as the shell type, the other as the core type.

In the shell type the coils are threaded through the magnetic circuit and are surrounded by it, while in the core type the coils surround the core. The usual form taken by the shell type is that shown in Fig. 37. It has been used to some extent in line transformers and very generally in connection with synchronous converters where air cooling is employed.

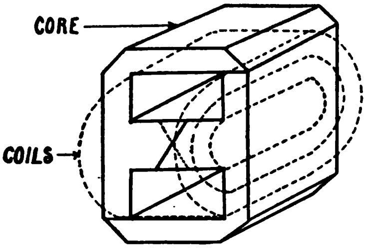



Fig. 37. Shell-type Transformer.

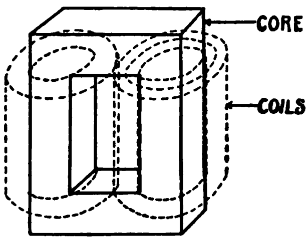



Fig. 38. Core-type Transformer.

The core type shown in Fig. 38 has been used very generally for line and transmission purposes where oil cooling is relied upon. The cylindrical form of the coils lends itself to dissipation of heat and application of insulation more readily than the flat type of coil used in the shell type. The core type has therefore been used very generally for distribution purposes.

In recent years a modification of the shell type shown in Fig. 39, known as the cruciform type, has been developed, which permits the retention of the cylindrical form of coil with the shell type of core. This form, which has been adopted by two leading American manufacturers, reduces magnetic leakage to a minimum, improves regulation and makes a very compact and efficient arrangement of copper and iron.

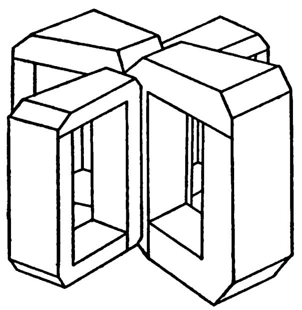


Fig. 39. Cruciform Shell-type Transformer.

In the construction of the magnetic circuit of the transformer the iron must be in sheet form to reduce the flow of eddy currents which tend to be set up by alternating magnetic flux. The sheet iron is commonly about .012 inch thick, this thickness having been found to be the most effective and economical. The shape of the stampings of sheet metal is carefully worked out so that they may be built up around the form-wound and insulated coils with facility. This must be done so as to affect the reluctance of the magnetic circuit as little as possible. The alternate laminations are therefore usually overlapped so that the magnetic lines of force do not have to cross a butt joint. The laminations are secured in position by bolts holding them rigidly in place.

**Core Material.** — The art of manufacturing sheet iron for use in making laminated magnetic circuits for alternating-current apparatus has made progress very steadily from the beginning of the industry. In the early years of alternating-current development the electrical manufacturer had nothing at his disposal in the way of sheet iron except the standard grades turned out for general purposes. It was found very soon that such iron when used in a transformer had magnetic properties which were variable with the length of time in service. The hysteresis loss per pound was high because of lack of proper annealing and varied widely in different lots because of the lack of uniformity in the heat treatment in the mill. The result was that a transformer which was reasonably efficient at the date of manufacture passed through a process of ageing which left it with a greatly increased hysteresis loss and reduced its all-day efficiency very materially. As soon as this phenomenon became well established, an endeavor was made to discover the cause of the ageing. The continued operation of the iron at higher than normal atmospheric temperatures seemed to be the seat of the trouble, and experi-

ments were therefore directed along the line of careful control of the heat treatment of the sheet metal during the process of manufacture to insure as perfect annealing as possible in the finished product. The accumulated experience of several years has produced gradual improvement in the magnetic properties of sheet iron, though ageing has not been entirely eliminated in pure sheet iron.

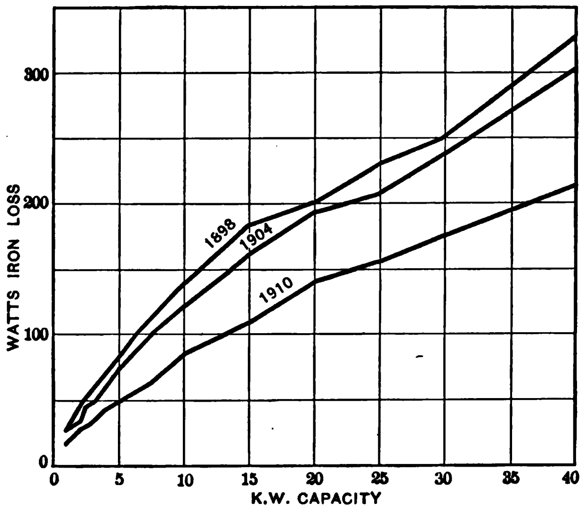



Fig. 40. Improvement in Iron Loss.

However, in recent years experiments in the manufacture of sheet metal from an iron and silicon alloy have reached a stage which is very promising, and transformers are being manufactured with cores made of this metal which not only permits the use of less core material but reduces the core loss and practically eliminates the ageing effect. Manufacturers of transformers have been able to change their transformer designs, reducing the cost of construction and producing more efficient apparatus.

The progress which has been made during the years 1898 to 1909 is made very plain by the curves in Fig. 40, which show the iron losses in the various sizes of line transformers at three points during this period.

**Copper Losses.** — The copper losses of the transformer assist in the production of heat while it is carrying load, and they must therefore be so limited as to keep the temperature of the interior of the transformer from rising more than 50 degrees C. above the surrounding air.

The elevation of temperature is determined by the radiation factor and by the energy losses. In an air-blast transformer, for instance, the dissipation of energy takes place more rapidly than in an oil-cooled unit because special facilities are provided for carrying off the heat generated.

The selection of cross-sections of copper for the windings is therefore fixed within certain limits by the heat losses therein, and by the means provided for their dissipation.

In the small sizes the large number of turns and the very small current in the primary coil allow the use of a lower-current density than is permissible in the larger sizes.

In the sizes above 5 K.W. the copper is usually run at from 400 to 500 circular mils per ampere at full load. These densities give full-load copper losses which are somewhat greater than the iron losses in the smaller sizes, while they amount to about twice the iron losses in the larger units.

**Heat Dissipation.** — The problem of disposing of the heat generated in a transformer is one which has required a great amount of study and experiment. In the beginning of the art when units were small, natural radiation into the air was sufficient. As sizes increased this was inadequate to keep down interior temperatures to a point where slow charring of

insulating materials would not take place. The air blast was naturally suggested as a means of hastening radiation and has found a useful field in stations and substations where attendance is continuous and floor space is limited.

This was not feasible, of course, for distribution work, and the use of a bath of oil around the coils was tried. This served the double purpose of excluding moisture and assisting radiation by the action of convection currents which cause the heated oil next to the coils to rise to the top, drawing the cool oil up from the bottom to take its place. This plan was soon found to be so effective both in cooling and insulating the coils that it became standard practice with all the principal manufacturers, and continues to be the method used for all line transformers and for station work where floor space is not limited or where the voltage of transmission is above 15,000. In the larger units, say 1000 K.W. and upwards, the size of the case necessary to hold oil sufficient to radiate the energy at the proper rate becomes excessive. It is therefore usual to provide a case of sufficient size to contain the transformer and cooling coils of pipe as shown in Fig. 41. The transformer and cooling coils are immersed in oil which serves to convey the heat from the transformer below to the coils above. Water is circulated through the cooling coils in proper quantities to carry away the heat liberated in the transformer. This method of cooling is readily applicable where a cheap supply of water is available. It is not so economical where a supply of water must be purchased at usual municipal water rates.

In very large units, 2500 K.W. and over, it is sometimes justifiable to provide a forced circulation of water or oil to carry away the heat. In such cases it may also be necessary to provide means for cooling the circulating liquid. Such problems are, however, special and must be worked out to suit local conditions.

In the design of the coils and cores of self-cooled oil-insulated transformers, it is important that they be so shaped and mounted on the core as to permit a free circulation of oil about them. For instance, in the core-type transformer the

Fig. 41. Water-cooled Transformers.

square corners may be used in conjunction with the cylindrical coils to provide open vertical channels or flues through which streams of oil may pass, thus reaching the inner parts of the coils and core, and preventing these parts from reaching a temperature very much higher than the outside parts as shown in Fig. 42.

In the shell type this is not so feasible, and radiation must be accomplished by flaring apart the coils at the ends where they turn so that the oil can reach them on both sides and by providing circulation slots between the coils.

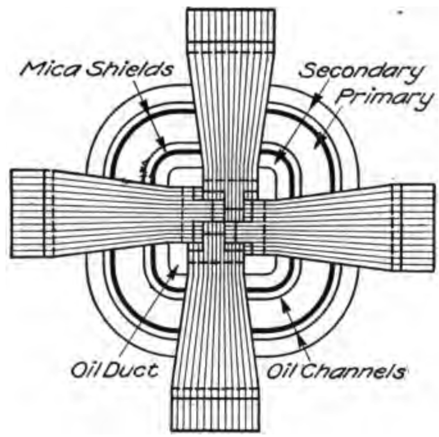



Fig. 42. Arrangement of Oil Ducts in Transformer.

The radiation of heat from the case is facilitated by vertically corrugated surfaces which may be so designed as to greatly increase the radiating surface without increasing the cubic contents of the case.

**Regulation.** — The regulation of a transformer is dependent upon its ohmic resistance and its inductive reactance. Fortunately the size of the conductor required to keep the rise of temperature within safe limits is sufficient to keep the ohmic drop in the transformer down to a point which is satisfactory for general purposes. The fall of pressure in the transformer is fixed by the same principles which govern an alternating-current circuit. The resultant of the ohmic and inductive drops is the impedance drop, or $Z = \sqrt{R^2 + X^2}$,

when $Z$ is impedance drop, $R$ is ohmic drop and $X$ is reactance drop.

The impedance drop is, however, not the actual regulation of the transformer except at that power factor which is the same as the ratio of $R$ to $Z$.

To determine the regulation at any power factor, the ohmic and reactance drops must be applied to the Mershon diagram. (See Chapter XV.)

The reactance drop cannot be calculated directly, but may be determined by test as follows: With the secondary terminals of the transformer short-circuited through an ammeter the pressure on the primary terminals is brought up until full-load current passes through the secondary ammeter. The pressure required to do this is the impedance drop. The resistance drop of primary and secondary is found by passing direct current through them and observing the voltage drop. The reactance drop is then found from the above formula, $X = \sqrt{Z^2 - R^2}$.

**Coil Insulation.** — The insulation of the coils of a transformer from each other and from the case is of supreme importance. In transmission work large amounts of power are dependent upon the reliability of the transformer, while in distribution work not only the central station service but the lives of consumers and the general public are dependent upon it to a large extent.

The conductors are double cotton covered, to separate the adjacent turns, while the layers are separated by a proper thickness of varnished cambric, sheet mica or other insulating material. The completed coil is wrapped with linen tape covering the cotton braid, after being impregnated with heated insulating compounds which drive off any remaining traces of moisture.

The primary and secondary coils being placed in close

proximity are separated from each other by mica and hard wood or fiber so as to provide an oil-filled gap between the coils. The coils are likewise separated from the core by sheets of mica and other material. The cylindrical type of coils used in core-type construction and in the improved shell type are easily protected by layers of mica, and are therefore the most reliable form of coil for distribution pur-

Fig. 43. Line Transformer Hangers.

poses. Forms which require the protection of sharp corners are more difficult to insulate safely. Mica is not affected by heat or moisture and therefore forms the best insulating material where it can be applied effectively in sheets.

Distribution transformers are commonly provided with rugged cast-iron cases adapted to stand exposure to the weather and to the rough handling incident to installation and removal at occasional intervals. They must be oil-tight,

as leakage is likely to result in claims for damages from property owners as well as very unsightly equipment. The cover is made removable for convenience in filling with oil and in changing the primary coil connections from series to multiple. Lugs are cast on the case to fit wrought-iron hangers by which they may be conveniently hung on a cross-arm, as shown in Fig. 43.

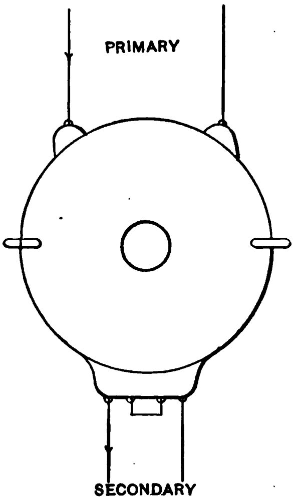


Fig. 44. Transformer Polarity.

**Polarity.** — It is customary in bringing out the leads of distribution transformers to follow a uniform method of connecting coils on primary and secondary sides so that units may be coupled in parallel by following a symmetrical plan of connections without testing for polarity every time. The polarity is made such that current is leaving the right-hand terminal of the secondary at the same instant that it is entering the transformer through the corresponding terminal of the primary, as shown in Fig. 44.

**Efficiency.** — The physical laws governing the magnetic characteristics of a transformer having an iron core are fortunately such that the relative amount of copper required is small, and the losses in the copper windings are not as great as they are in a generator or synchronous converter. The lack of moving parts further tends to make the transformer one of the most efficient pieces of electrical apparatus in general use.

The efficiency of a transformer which is used in transmission work is of most importance at the time of full load

since it usually carries its load several hours per day, and its iron losses are a small part of its converted output. It is important, therefore, that its copper losses be low and its full-load efficiency as high as possible. In a distribution transformer supplying its full lighting load but two to four hours per day, the full-load efficiency is less important, while the iron loss which goes on 24 hours may become a considerable percentage of the daily output of the unit.

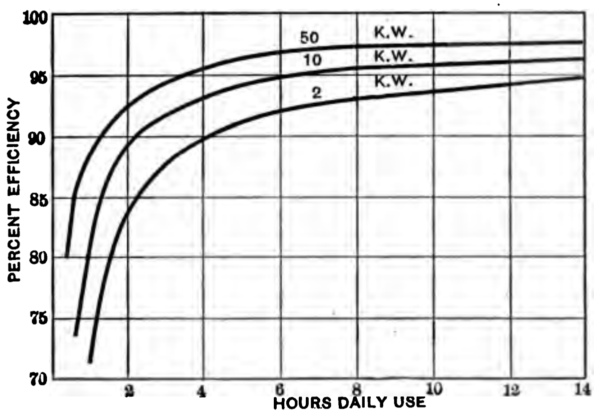



Fig. 45. All-day Efficiency of Transformers.

For instance, in the case of a 5-K.W. transformer which delivers 20 K.W. hours per day, the copper loss would be about 100 watts at full load, while the iron loss would be about 50. The copper loss per day would be about 400 watt hours, while the iron loss would be $24 \times 50 = 1200$ watt hours. The total loss being 1600 watt hours, the all-day efficiency is $\frac{20}{21.6} = 92.6$ per cent, while that at full load is $\frac{5000}{5150} = 97.1$ per cent. It is apparent that the all-day efficiency varies with the load factor or hours' use of the maximum load. The efficiency at various load factors is shown for several sizes of transformers in the curves in Fig. 45. It

is evident from these curves that a system in which there are a considerable number of 1-K.W. transformers will have a lower all-day efficiency than one in which the same amount of load is supplied by 5-K.W. transformers. The average size of transformers should therefore be kept as large as consistent with a reasonable investment in secondary mains.

The average values of efficiency, copper loss, iron loss and regulation of the line of distribution transformers of the improved shell type made by the leading American manufacturers are shown in the following table: —

| K.V.A. | Watts loss. | | Per cent efficiency, full load. | Per cent regulation. | | Per cent leakage current. |
|---|---|---|---|---|---|---|
| | Core. | Copper. | | 100 per cent P.F. | 80 per cent P.F. | |
| 1 | 20 | 24 | 95.8 | 2.42 | 3.12 | 5.5 |
| 1½ | 25 | 34 | 96.2 | 2.28 | 3.01 | 4.0 |
| 2 | 30 | 42 | 96.5 | 2.12 | 2.88 | 3.6 |
| 3 | 34 | 64 | 96.8 | 2.16 | 2.91 | 3.0 |
| 4 | 40 | 75 | 97.2 | 1.90 | 3.00 | 2.5 |
| 5 | 45 | 93 | 97.3 | 1.90 | 2.99 | 2.3 |
| 7½ | 62 | 125 | 97.6 | 1.70 | 2.84 | 2.2 |
| 10 | 80 | 148 | 97.8 | 1.51 | 2.68 | 1.9 |
| 15 | 105 | 212 | 97.9 | 1.44 | 2.63 | 1.6 |
| 20 | 131 | 268 | 98.0 | 1.39 | 2.87 | 1.5 |
| 25 | 147 | 319 | 98.2 | 1.33 | 2.82 | 1.3 |
| 30 | 163 | 374 | 98.2 | 1.32 | 2.82 | 1.2 |
| 40 | 205 | 433 | 98.3 | 1.20 | 2.72 | 1.2 |
| 50 | 240 | 550 | 98.4 | 1.15 | 2.68 | 1.0 |

The copper loss and regulation figures in the above table are based on a temperature of 77 degrees F., whereas under the normal condition of full-load operation the temperature of the windings is about 150 degrees F. The increase in the resistance of copper being about .22 per cent per degree of rise, the increase in resistance at 150 degrees would be 73 × .22 = 16 per cent. The copper losses at 150 degrees would therefore be about 16 per cent higher than the values shown in the above table and the regulation would be proportion-

ately increased. In a 5-K.W. transformer the copper loss would be $93 \times 1.16 = 108$ watts, while the regulation at 100 per cent P.F. would be $1.9 \times 1.16 = 2.2$ per cent.

**Three-phase Units.** — In three-phase systems the possibility of saving a part of the core material and reducing the cubic feet occupied has led to the adoption of three-phase

Fig. 46. Three-phase Air-cooled Transformer.

units in some kinds of work. The three-phase unit as worked out in the shell type with air-blast cooling is shown in Fig. 46. This unit effects a saving in floor space and in first cost which has made it standard for synchronous converter work. In the core-type unit illustrated in Fig. 47 the cooling is effected by oil, and this type is used in distribution work or in situations where attendance is not continuous. It is not usual to attempt to use a three-phase unit smaller than 15 K.W. Having the three phases contained in one case they are made

in larger capacities than single-phase units, having been made as large as 7500 K.W. for use in transmission work.

For general distribution purposes the three-phase unit in sizes less than 150 K.W. has some serious limitations. It puts the entire load furnished by the unit out of service if any trouble develops in either phase of the unit, and the expense of providing a substitute unit is necessarily greater.

Fig. 47. Three-phase Oil-cooled Transformer.

Where transformers of all sizes must be kept on hand to take care of light and power service it is more flexible to have single-phase units which are available for either light or power than to attempt to carry a line of single-phase units for lighting and three-phase units for power.

In construction work where the transformers are hung on poles it is easier to distribute the weight of the transformers on the pole with three units than with one in installations of

50 K.W. or more. In underground work the saving in space is of value in a manhole, but the shape of the three-phase unit is such that it cannot be installed or removed unless a special size manhole cover is used.

The three-phase unit has not, therefore, been generally used in distribution work, except where local conditions make it compulsory.

In the design of the core of three-phase units some saving in the weight of core metal is possible when the middle phase is connected in reversed order so that the magnetic fluxes of the adjacent phases do not combine in the usual 120 degrees relation but at 60 degrees apart.

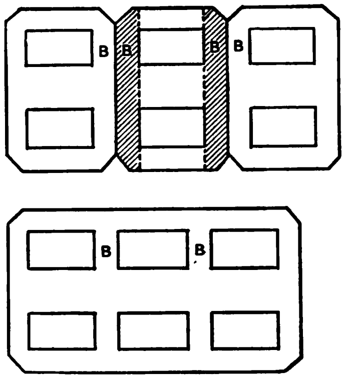


Fig. 48. Single and Three-phase Cores, Shell Type.

For instance, the shell-type unit, as shown in Fig. 48, may be designed with the same cross-section at *B* as each of the three single-phase units has at the points *B*, thus saving the shaded portion of the middle single-phase core.

## CHAPTER V.

### SECONDARY DISTRIBUTION.

**Historical.** — In the early stages of the introduction of alternating-current systems the use of 52 to 55 volt secondary circuits was advocated by some engineers because of the superior life of incandescent lamps of these voltages. Such a voltage was not permissible in direct-current work because of the excessive amount of copper required, but could be used in alternating-current systems because of the possibility of locating transformers close to the customer's premises. At this voltage, however, it was not possible to supply more consumers from one transformer than could be reached from the pole on which the transformer was placed without an excessive use of copper. The result was a system in which a large number of small transformers were required. These consumed an excessive amount of energy in their cores and required the operation of extra generating capacity at times to supply their large leakage currents.

As soon as these distributing systems attained such size that these items became an appreciable expense, a remedy was sought. The higher voltage lamp having been improved, 110-volt secondaries were introduced and the 55-volt consumers were gradually changed over to 110 volts. The use of the higher voltage increased the range of distribution so that a single 110-volt transformer was installed to replace several 55-volt transformers, with a saving in the amount of capacity required and a very great saving in the core losses and leakage currents.

Later the availability of the Edison three-wire system for

general secondary distribution increased the range of such lines by permitting the use of 110–220 volt mains, with 110-volt lamps.

At this voltage distribution may be economically made from transformers spaced 800 to 1000 feet apart in some cases, and a spacing of 400 to 600 feet is very common. This greatly increases the number of consumers which can be supplied from a single unit, and permits a great saving in investment as well as in iron losses since the concentration of a given kilowatt capacity in a single unit costs less than the same capacity in several smaller units and requires much less energy to supply the iron losses. For instance, in replacing five 3-K.W. units, with one 15-K.W., there would be a saving of about $60 in investment and 50 watts in the all-day losses, which is 33 per cent of the investment and 25 per cent of the iron losses.

Furthermore the diversity of habits of use of electricity of a large number of consumers is such that the maximum demand on the transformer which covers 1000 feet of line is much less than the sum of the maxima of five units covering 200 feet each, other things being equal. The advantage thus gained from what is known as the diversity factor often permits a saving of 40 to 60 per cent in the investment in transformers as compared with house-to-house transformers.

The three-wire system is used for single-phase secondary distribution very generally in American cities in sections where there are a number of consumers grouped within economic range of a transformer. Two-wire distribution may be used where consumers are so scattered that there is no advantage in the three-wire system.

**Periods of Development.** — A system of secondary mains passes through three general periods of development in expanding from a small to a large system.

(1) A period in which scattered transformers supply isolated secondary mains not interconnected with other transformers.

(2) A period in which the mains from adjacent transformers grow together along principal thoroughfares where they may be connected to each other but intersecting few other secondary mains of importance.

(3) A final stage in which secondary mains are required on nearly all streets and are therefore joined into a network.

The first period is that found in residence and other outlying territory not fully built up. When a new consumer is to be connected in such a territory the problem is — Shall a transformer be installed or the nearest secondary main extended to the premises? The installation of a transformer involves an investment and an operating expense, due to its core loss. The extension of the nearest secondary main involves an investment in conductors and perhaps an increase in the capacity of an existing transformer. The cost of the two alternative plans being ascertained, the one selected should be that which involves the least annual cost for interest, depreciation and operation. For instance, assume that service is required for a new consumer, with a load of 1 K.W., at a point where there is no secondary main available. Also, that if a separate transformer is installed the investment will be about $30, and if the nearest secondary main is extended the expenditure will amount to $40. How shall service be given?

If the $30 investment is made there will be fixed charges of interest and depreciation at the rate of 15 per cent, amounting to $4.50 per annum. There will also be an operating expense, due to the core loss of a 1-K.W. transformer of about 30 watts 8760 hours per year, or 263 K.W. hours. At 1 cent per K.W. hour this amounts to $2.63, and the total annual cost is $7.13.

Were the $40 expended for a secondary main, the fixed charges at the rate of 10 per cent are $4, and no operating expense is added unless it be required to increase the capacity of the transformer then installed. If it is necessary that 1 K.W. be added to the capacity of the existing transformer, the expenditure would be increased about $8, adding a fixed charge of $1.20 and an operating expense of about 10 watts or 87 K.W. hours per year, costing 87 cents. The cost per year under this plan is therefore $4 in case the existing transformer can take the added load without change, or $6.07 if it cannot. In this case it would therefore be preferable to extend the secondary rather than to install a separate transformer.

There is little occasion in this period of development to connect secondary mains in multiple. Where the mains have been extended until they meet each other it is usually preferable not to interconnect them, as the blowing of the fuse of either transformer shifts the load to the other, and overloading it blows its fuse also; and transformers are so far apart that they cannot assist each other to any appreciable extent in case of an overload on either of them.

The second period of development is reached when consumers become so closely situated that it is necessary to provide a continuous secondary main along a thoroughfare. This condition is usually first met along business streets and boulevards, and results in a long secondary main fed at intervals by transformers but intersected by few other secondary mains of importance. When such a main has been established it is the problem of the engineer to determine how far apart transformers should be located and what size of conductor should be used.

The density of the load varies in different parts of the street, and there are large blocks of load at particular points which make the problem a perplexing one at best. A general

solution is usually not possible, owing to the widely varying local conditions. However, a determination may be made which will serve to indicate the approximate limits within which the most economical arrangement of transformers and wire will lie, and from which some general principles of value may be deduced.

**Calculation of Continuous Main.** — Assuming that an overhead three-wire 115–230 volt secondary main 6000 feet in length is uniformly loaded at intervals of 100 feet, what will be the best size of wire and distance between transformers? For a given load density, say 50 K.W. per 1000 feet of line, the supply of electricity may be distributed from several small transformers, with small wire and short spacings between units, or from fewer units with larger wire and longer spacings. The use of many units tends to increase the transformer investment and the all-day losses, while the investment in conductors tends to be lessened. It is therefore possible to find a point where the sum of these conflicting influences is a minimum.

In the figures given in detail in Table II the calculation is based on 2 per cent maximum voltage drop on the secondary main, with overhead lines, weatherproof wire at 15 cents per pound, energy at 1 cent a K.W. hour, fixed charges on transformers at 15 per cent and on conductors at 10 per cent. The iron losses are assumed to go on through 8760 hours per year. With 50 K.W. per 1000 feet, when No. 6 wire is used, the transformers must be 400 feet apart to keep the drop within 2 per cent. Fifteen units of 20 K.W. each are required for the assumed length of 6000 feet. Their iron loss is 2400 watts, so that the annual loss is 2400 × 8760 = 21,000 K.W. hours. At 1 cent this will cost $210 per year. The value of fifteen 20-K.W. transformers is about $2250 and 15 per cent of this is $338. The value of 18,000 feet of No. 6

TABLE II. — COST OF SECONDARY DISTRIBUTION.

50 K.W. per 1000 Feet.

| Distance between transf., Feet. | Size of cond., B. & S. G. | No. of trans. | Size of trans., K.W. | 15 per cent on trans. | Value iron loss. | Underground. | | Overhead. | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 10 per cent on cable. | Total annual cost. | 10 per cent on wire. | Total annual cost. |
| 400 | 6 | 15 | 20 | 338 | 210 | 171 | 719 | 30 | 578 |
| 500 | 4 | 12 | 25 | 315 | 198 | 198 | 711 | 44 | 557 |
| 600 | 2 | 10 | 30 | 300 | 183 | 234 | 717 | 67 | 550 |
| 1000 | 4/0 | 6 | 50 | 278 | 157 | 520 | 955 | 217 | 652 |
| **100 K.W. per 1000 Feet.** | | | | | | | | | |
| 300 | 4 | 20 | 30 | 600 | 375 | 198 | 1173 | 44 | 1019 |
| 400 | 2 | 15 | 40 | 576 | 342 | 234 | 1152 | 67 | 985 |
| 500 | 0 | 12 | 50 | 555 | 314 | 333 | 1202 | 110 | 979 |
| 600 | 2/0 | 10 | 60 | 525 | 304 | 385 | 1214 | 133 | 962 |
| **150 K.W. per 1000 Feet.** | | | | | | | | | |
| 300 | 3 | 20 | 45 | 825 | 487 | 232 | 1544 | 56 | 1368 |
| 400 | 1 | 15 | 60 | 765 | 444 | 285 | 1494 | 88 | 1297 |
| 500 | 2/0 | 12 | 75 | 720 | 409 | 385 | 1514 | 133 | 1262 |
| 600 | 4/0 | 10 | 90 | 675 | 385 | 520 | 1580 | 217 | 1277 |
| **150 K.W. Four-Wire Three-Phase.** | | | | | | | | | |
| 400 | 2 | 45 | 20 | 1013 | 626 | 312 | 1951 | 90 | 1729 |
| 500 | 0 | 36 | 25 | 946 | 565 | 444 | 1955 | 146 | 1657 |
| 600 | 2/0 | 30 | 30 | 900 | 548 | 513 | 1961 | 178 | 1626 |
| 750 | 3/0 | 24 | 37.5 | 870 | 513 | 600 | 1983 | 230 | 1613 |

weatherproof wire is about \$300 and 10 per cent of this is \$30. The total annual cost is therefore 210 + 338 + 30 = \$578. In a similar way the calculations have been carried through for No. 4 wire with twelve 25-K.W. transformers, for No. 2 with ten 30-K.W. and for 4/0 cable with six 50-K.W. units spaced 1000 feet apart.

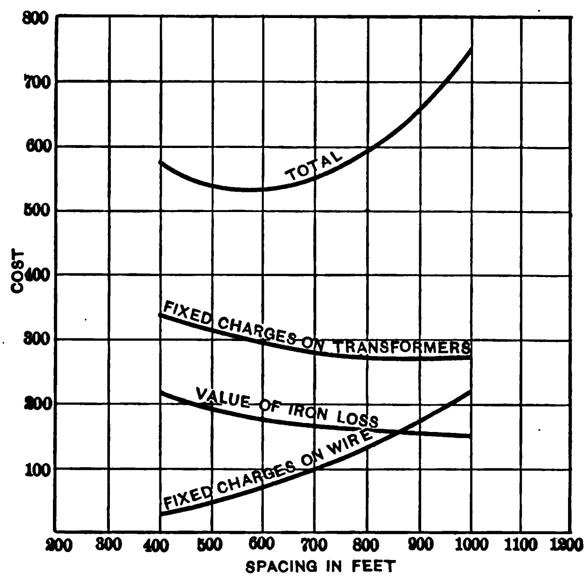



Fig. 49. Elements of Annual Cost, Secondary Main.

The calculations have also been made for load densities of 100 and 150 K.W. per 1000 feet of line on the Edison three-wire system with neutral full size, and for 150 K.W. per 1000 feet on the four-wire three-phase star-connected system with all wires the same size.

The manner in which the various elements of cost vary as the spacing between transformers and size of wire is increased is illustrated by the curves in Fig. 49, which are based upon the values obtained in the calculations made for a load density

of 50 K.W. per 1000 feet, with overhead lines. It is apparent from the curve of total cost that the minimum is found with No. 2 wire, which gives a spacing of 600 feet between transformers, though No. 4 wire with 500 feet spacing is nearly as economical.

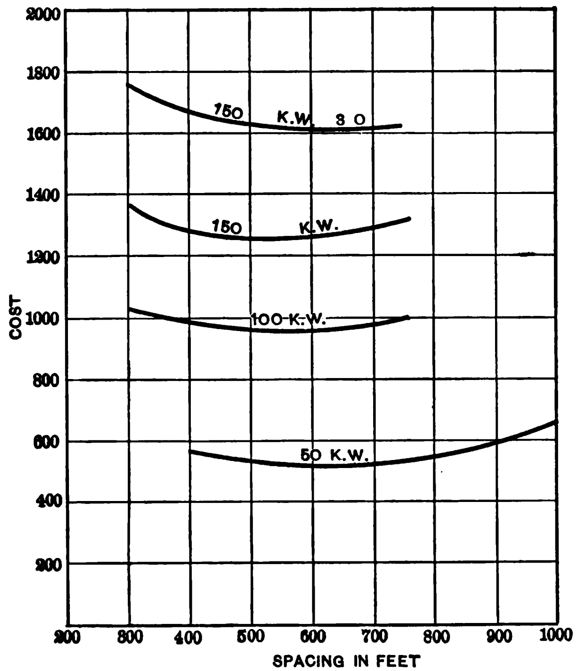



Fig. 50. Economical Transformer Spacing, Overhead Mains.

The curves of total cost at densities of 50, 100 and 150 K.W. per 1000 feet and for 150 K.W. three-phase four-wire are shown in Fig. 50. It will be seen from a study of these curves and the table of figures that with overhead lines, under the conditions assumed, the most economical spacing of transformers is from 500 to 600 feet apart at all ordinary load densities. Where energy is generated at less than

1 cent per K.W. hour, or with water power, the value of core loss is a diminishing factor, which tends to permit the use of smaller transformers, shorter spacings and smaller size of wire. With water power the spacing may be reduced to about 400 feet between transformers.

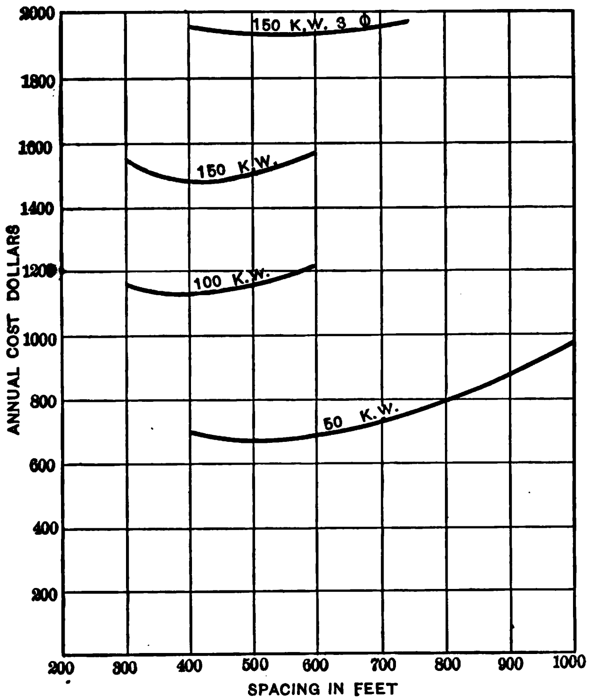



Fig. 51. Economical Transformer Spacing, Underground Mains.

The calculation for underground lines is also included in Table II and is shown graphically in Fig. 51. The most important difference between these figures and those for overhead lines is in the cost of conductors. The figures are based on single-conductor lead-sheathed paper-insulated cables with $\frac{4}{32}$ insulation over each conductor and copper at 15 cents per pound. The absolute values of annual cost are

from 20 to 25 per cent higher than with overhead lines, but the spacing for the minimum value is not materially changed, it being about 500 feet for each load density. The fact that the best spacing power proves to be about 500 feet is a fortunate one in many cities where this is the approximate length of a city block. The location of transformers at street intersections is especially desirable where the lines are on streets, as it permits of the supply of electricity in four directions from one unit. With alley lines which do not intersect other secondary mains the best location is often near the middle of the block. The flatness of the curve of total cost allows considerable flexibility in spacing, and it is generally preferable to use as few transformers as possible with the larger sizes of conductor, so as to reduce the number of units to a minimum. The curves indicate that this can be done if desired without seriously affecting the economy. Furthermore, it is usually desirable in building extensive secondary mains to anticipate an increase in load, by erecting a larger conductor than is required for immediate needs. This may be done at the start and the size of transformers gradually increased as the load increases.

Further growth must then be provided for by the replacement of the overloaded portions of the main by conductors of a larger size.

The entire foregoing discussion is based on an assumption that the load is evenly distributed along the line throughout its length.

However, such is not the case in practice. It is more often that portions of a secondary main are heavily loaded, while other portions carry a more scattered load owing to differences in the character of the neighborhoods through which it passes. At occasional intervals department stores, churches or other large consumers of electricity throw heavy loads upon the line.

It is therefore necessary in practice to locate transformers as closely as possible to such large consumers' premises and design the main between them to carry the scattered consumers whose load is approximately evenly distributed. An extended secondary main may therefore be made up of several sizes of wire at different points with transformers having various spacings, depending upon the load density in the vicinity.

The design of the various portions of such a secondary main may be considerably facilitated if the general theory outlined in the foregoing is taken into consideration and intelligently applied.

**Networks.** — The network is the last step in the development of a system of secondary mains. The gradual extension of mains on all intersecting streets results in a system of lines which is interconnected at intersecting points and thus becomes a network.

Transformers are located at points of intersection where they deliver current in all directions with the best economy of copper. The transformers thus supply practically feeder end pressure at all junction points where they are placed, as the primary mains are so short that there is no appreciable drop in them. This is an advantage over a direct-current network where the feeders are connected to the network in only one or two places, and the low-tension mains must have greater capacity in order to maintain an even pressure throughout. A common arrangement of feeders, mains, transformers and secondary network is shown in Fig. 52.

In the design of such networks the selection of sizes of secondary cable is restricted by the practical conditions in each locality. The smaller distributed consumers are carried from mains of proper size to deliver the energy demanded. Large consumers such as theaters and department stores are

usually more economically cared for by a separate installation of transformers in the immediate vicinity of the consumers' premises. The nature of the locality is usually such that underground construction is required where a network exists. This necessitates manholes of ample size for large transformers and such other junction boxes as are necessary for the proper operation of the system. The space required is sometimes difficult to secure on account of gas and water pipes,

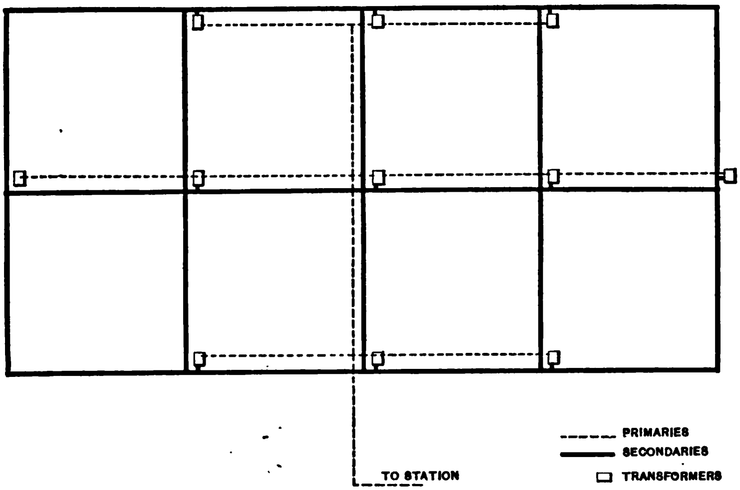



Fig. 52. Alternating Current, Secondary Network.

car tracks and other underground systems which limit the clear space. It is not desirable to go below such obstructions as the manhole should be able to drain into a sewer, and therefore should not be below the sewer level.

In some localities it has been found that these difficulties were sufficient to warrant the segregation of the transformers in a basement substation, supplying the network through low-tension feeders varying in length from 300 to 1000 feet. This arrangement permits a considerable saving in transformer investment and iron losses, as the diversity factor is

better, the units are larger and the transformer capacity may be varied from hour to hour to suit the demand, thus saving considerable energy loss.

**Inductive Loads.** — The design of secondary systems is subject to some restriction when inductive loads, such as arc lamps and motors, must be served along with incandescent lighting.

The regulation of transformers is not so good with inductive load as with noninductive load, owing to the reactive drop in their windings. In case power and lighting loads are supplied from the same transformer the heavy starting current required by the induction motors momentarily overloads the transformer with current at a low power factor. This low power factor current drops the pressure on the secondary line for a few moments and causes a flickering of the incandescent lights. If the motor load is a considerable part of the total load the pressure remains lower while the motors are in operation and varies as the motor load changes. It is therefore necessary to install separate transformers for power load and for large installations of arc lamps where these constitute a majority of the load, if the best regulation is required for incandescent lighting.

**Regulation of Transformers.** — The regulation which will be secured with a given transformer may be calculated for any set of conditions which may arise, if the impedance drop of the transformer is known. For instance, assume a 10-K.W. transformer wound for 2200–110 volts with an impedance drop of 80 volts or 3.6 per cent, also that the ohmic drop in the primary and secondary coils measured by means of direct current is 1.8 per cent or 40 volts, at full load. The reactance drop is

$$X = \sqrt{(80)^2 - (40)^2} = \sqrt{6400 - 1600} = 69 \text{ volts} = 3.1\,\%.$$

In Fig. 53 let $OA$ be the impressed pressure on the primary at no load. $AB$ is the ohmic drop in the transformer windings, which in this case is 40 volts. This is in opposition to the impressed E.M.F., and must therefore be added directly to it in determining what pressure must be impressed on the transformer in order to deliver its rated secondary pressure at full load. $BC$ represents the inductive drop of 69 volts which must be laid off at right angles to $AB$. The pressure necessary to secure 110 at the secondary at full load is therefore $\sqrt{(2240)^2 + (69)^2} = 2241$ volts. With an incandescent lamp load of 100 per cent power factor the regulation of this transformer is $2241 - 2200 = 41$ volts or 1.8 per cent.

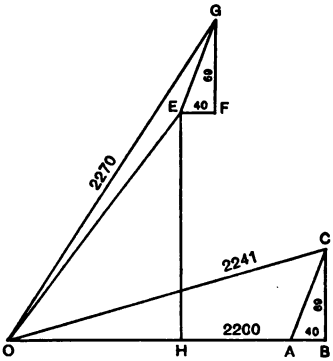


Fig. 53. Transformer Regulation, Inductive Load.

With a load of 10 kilovolt amperes at 70 per cent power factor the regulation is calculated thus:

In Fig. 53 the impressed pressure 2200 volts at no load is $OE$. This is opposed by a power-consuming component in the load carried $OH = .7 \times 2200 = 1540$ volts, and a wattless component $EH = .71 \times 110 = 1562$ volts. The ohmic drop in the transformer $EF = 40$ volts and the inductive drop $FG = 69$ volts. The impressed pressure at the primary necessary to maintain 110 volts at the secondary of the transformer is therefore

$$OG = \sqrt{(OH + EF)^2 + (EH + FG)^2},$$

$$OG = \sqrt{(1580)^2 + (1631)^2} = 2270 \text{ volts}.$$

The drop at 70 per cent power factor is $2270 - 2200 = 70$ volts $= 3.2$ per cent. At 100 per cent overload this would

be 6.4 per cent. With a motor taking two or three times full-load current at a power factor of 70 per cent or less at starting, it is evident that incandescent lights supplied by the same transformer will flicker whenever the motor is started and will burn at reduced candle power while the motor is running, unless the motor load is so small compared with the lighting that the starting current is less than the full-load current of the transformer.

With a load consisting of arc lamps, the power factor of which is 75 to 80 per cent, the drop at full load would be about 3.0 per cent. This would be considered too much for satisfactory incandescent lighting in many cases, and if so it would be necessary to set a separate transformer for the arc lamps. When combined with an equal amount of incandescent lighting, the resulting power factor at the transformer is increased to about 95 per cent and the regulation of the transformer is within proper limits for satisfactory lighting.

Table III shows some of the characteristics of line transformers of the sizes commonly used, which will be of use in making calculations. Improvement has been made by reducing the reactance drop in the smaller sizes of transformers in recent years.

TABLE III. — REGULATION AND LOSSES OF LINE TRANSFORMERS.

| Capacity, K.W. | Iron loss. | Copper loss. | Ohmic drop, per cent. | Per cent regulation at 80 per cent P.F. | Regulation at 100 per cent P.F. |
|---|---|---|---|---|---|
| 1 | 20 | 24 | 2.4 | 3.12 | 2.45 |
| 1.5 | 25 | 34 | 2.4 | 3.02 | 2.45 |
| 2 | 30 | 42 | 2.1 | 2.9 | 2.15 |
| 3 | 34 | 65 | 2.1 | 2.9 | 2.15 |
| 4 | 40 | 75 | 1.92 | 3.00 | 1.95 |
| 5 | 45 | 94 | 1.9 | 3.00 | 1.95 |
| 7.5 | 62 | 125 | 1.72 | 2.85 | 1.75 |
| 10 | 80 | 150 | 1.5 | 2.7 | 1.55 |
| 15 | 105 | 212 | 1.42 | 2.65 | 1.45 |
| 20 | 131 | 268 | 1.36 | 2.85 | 1.39. |
| 25 | 147 | 320 | 1.3 | 2.82 | 1.33 |
| 30 | 163 | 378 | 1.26 | 2.80 | 1.30 |
| 40 | 205 | 433 | 1.2 | 2.75 | 1.23 |
| 50 | 240 | 550 | 1.1 | 2.7 | 1.15 |

**Mains for Power Service.** — The installation of separate transformers for power load necessitates separate secondary systems for power consumers whose premises are in the same vicinity. The design of such mains is governed by the same principles that control the arrangement of lighting mains, except that it is permissible to allow the secondary line drop to be 5 per cent or more instead of 2 to 3 per cent required for satisfactory incandescent lighting. This permits power secondary mains to be extended to about twice the permissible range for incandescent lighting. In manufacturing districts the power load usually exceeds the lighting, and duplicate secondary systems are frequent though not close enough together to permit interconnection to any extent. In mercantile districts the reverse is the case, and the heavy lighting secondary system is capable of absorbing some miscellaneous power without seriously affecting the lighting service. The use of separate transformers for power in such sections is therefore not necessary except for occasional large consumers. Where separate secondary mains are maintained for arc lighting they may be designed for 5 per cent drop or more if necessary, as arc lamps may be adjusted somewhat for different voltages.

**Polyphase Systems.** — In two-phase systems it is usual to operate the lighting single-phase with two-wire and three-wire mains, as this is the simplest and most economical plan. The two-phase power service is supplied from separate transformers. In a few large two-phase systems where light and power are carried on the same underground secondary systems, two extra conductors have been provided from the other phase for two-phase power consumers, making a five-wire secondary system and five-wire services where light and power are served in the same building.

In three-phase systems two methods of carrying mixed

light and power load are available. The most commonly used consists of star-connected transformers supplying a four-wire main operated at about 115 volts from phase to neutral and 200 volts across phase wires. Lights are balanced as nearly as possible on the three phases. The smaller lighting services are two-wire, while larger ones are made three-wire, and connected to two phases and neutral and very large consumers are connected on three phases. Four-wire service is required for such customers and wherever both light and power is to be served in the same building. The objections

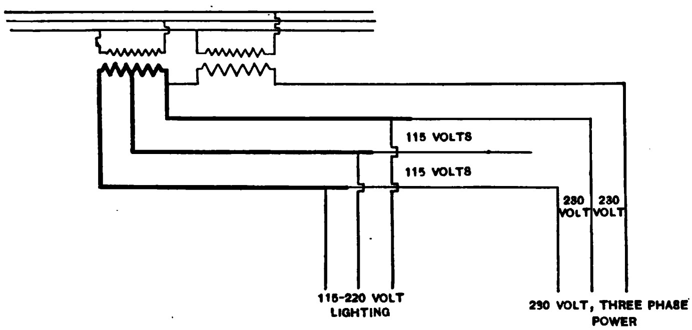



Fig. 54. Lighting on One Phase of Three-phase Secondary.

to this system are the difficulty of maintaining a balance and the necessity of installing three transformers at each point where the secondary main is fed.

In the other method, which is illustrated in Fig. 54, all the lighting is carried on one phase by means of a three-wire Edison secondary. Small power may then be served by the installation of one additional smaller transformer and a fourth secondary wire operating on the open delta connection. Larger power may require two power transformers in addition to the lighting transformer. The lighting in this system is easier to keep balanced, and since it is all on one phase the higher diversity factor requires less transformer capacity for

lighting purposes. This reduces transformer investment and core loss materially as compared with the star-connected secondary, as the average size of the units is larger and the total capacity required is somewhat less.

It will be noted in the calculations made for the most economical size of wire in Table II, that in the case of a load density of 150 kilowatts per 1000 feet on the four-wire three-phase system the minimum annual cost of such a system underground is $1950 as compared with $1494 for an Edison three-wire system under the same conditions. This difference is due to the fact that three transformers of small capacity are required in the three-phase system as against one in the single-phase. The saving in copper due to the use of three-phase secondary transmission is therefore much more than offset by the increased cost of transformers and greater iron losses.

Another advantage of carrying all lighting on one phase is that the effect of the starting current of motors is noticed less on the lighting supplied by the large unit than it is where the starting current is drawn from three smaller transformers, each of which carries lighting load. It is therefore possible with this system to carry larger power loads interconnected with the lighting than in the star-connected system under the same conditions.

Where a network has been developed, this system cannot be interconnected with other secondary mains except those which are fed from the same primary phase. Under these conditions it is necessary to sectionalize the network so as to divide the load between the primary phases. As the size of the mains in the network increases this becomes undesirable and the objections to the star-connected system become less important. The four secondary conductors may then be changed over to a star-connected system, using the three heavy conductors which were formerly used for lighting as

the outer wires of the new system and the power wire as the neutral. The network may then be interconnected throughout and increased reliability of service thus secured.

The use of combined light and power secondary mains becomes desirable in an underground system as soon as there is a sufficient number of power consumers to require a general system of power secondaries in any locality.

The expense of extra ducts and separate cables for separate power secondaries soon becomes excessive, and it is therefore found desirable to combine light and power secondaries into one system at an earlier stage of development than in the case of overhead lines.

**Determination of Transformer Capacity.** — The selection of the proper size of transformer for the supply of various classes of consumers is a matter of great importance since excess capacity involves idle investment as well as unnecessary core losses. The size of transformer units should therefore be kept as low as possible, consistent with preservation of the apparatus and good regulation.

Very few electric light and power consumers use their entire connected load at any one time. In lighting there are always some lamps which are not in use at times when the principal part of the lighting is on, and in power installations the maximum load is usually less than the rated capacity of the motors.

Where a number of consumers are grouped on one transformer the maximum demands of the various consumers do not occur simultaneously and the resultant maximum demand must be ascertained by measurements. These measurements may be made by means of a split-ring current transformer and ammeter or by the installation of a Wright demand indicator. The use of the demand indicator is preferable as it may be left in circuit throughout any desired period and the absolute

maximum for the entire period thus determined, whereas readings taken with an ammeter give results which are applicable only to the time at which the readings are taken. Certain ratios of maximum demand to connected loads may be established by a series of such measurements for the various classes of consumers for which it is necessary to select transformers. These ratios may then be applied with reasonable certainty to the selection of transformers for new consumers.

It has been found in practice that in store lighting the maximum demand for window lighting, signs and other display lighting is from 90 to 100 per cent of the connected load. The demand on interior store lighting is 50 to 70 per cent. There are but two or three nights in the week usually in which the demand is as much as 70 per cent.

In residences where the connected load is 50 lights or more the average maximum demand of a group of residences is 15 to 20 per cent of the connected load. Individual residences may have occasional maxima of 40 to 60 per cent, for which some allowance should be made in selecting transformer capacity. The size of the transformer may be such that it will be overloaded 25 to 50 per cent by the occasional high maximum of the largest individual consumer together with the average maximum of the other consumers on the transformer.

Small residences and apartments having connected loads of 40 lights or under average about 20 per cent of the connected load at the time of the daily maximum.

In general a higher ratio must be used where there are but two or three consumers on a transformer than where there are more, as the occasional maxima of individual consumers are a much larger percentage of the total.

In the case of churches and similar public buildings, capacity must be provided for the illumination of the largest room in the building together with the necessary hallways and

corridors. This usually requires capacity for at least 60 to 75 per cent of the connected load.

In theater lighting allowance may be made for the border and footlights of several colors which are not used simultaneously and for the fact that the stage and auditorium are not lighted simultaneously except for a very few minutes at a time. In a small theater the ratio may be from 70 to 85 per cent while in a large theater it frequently runs as low as 50 per cent.

Where several classes of buildings are fed by one transformer the capacity must, of course, be determined by taking each class into consideration separately and thus arriving at an average ratio for the whole.

The selection of transformers for power consumers is a more difficult task, as the maximum load may vary greatly from day to day or from month to month. The maximum load should be estimated where possible from the nature of the work done rather than from the motor rating, as motors are frequently chosen with reserve capacity. Elevator and crane motors require transformers of 100 to 125 per cent of their rated capacity unless there are several motors supplied by one unit. This is necessary in order to hold up the pressure in starting. The load of such equipments is so intermittent that heating is usually not a factor in determining the size of the transformer.

From data given by Lloyd in the proceedings of the 1909 convention of the National Electric Light Association (p. 588, Vol. II), the maximum demand of the average power consumer having a single motor is from 65 to 85 per cent of the rated capacity in installations of 10 horse power and less, and from 55 to 60 per cent with larger motors.

Where the installation consists of two to five motors the maximum demand is from 55 to 80 per cent, the lower figure being applicable to installations having motors of 20 horse

power and larger. Where there are over five motors the maximum demand is from 45 to 65 per cent of the connected load.

These figures were made up from several thousand installations of direct-current motors in Chicago, which were equipped with maximum demand meters. They may be considered as representative, as they embrace every kind of manufacturing work which is commonly supplied by central station systems.

# CHAPTER VI.

## SPECIAL SCHEMES OF TRANSFORMATION.

THE use of various distributing primary and secondary voltages and of single, two and three-phase systems give rise to situations at times which require the distributing engineer to resort to various unusual devices to fit these together with standard apparatus.

A breakdown in an industrial plant may make it necessary to get quick action in furnishing power from the central station system. The ability to make such connections promptly may be a factor in impressing the industrial concern with the advantages of drawing its supply from the distributing system permanently. Or conditions may arise when it becomes desirable to be able to render service to a consumer who has been securing his service from a competitor on a different system.

Such situations cannot always be easily met since a change from the direct to alternating current, or other conditions which necessitate a change in motors, involve an expense which is likely to be prohibitive.

However, there are situations which can be met with comparative ease, with standard apparatus and special connections which should be sufficiently familiar to the engineer to enable him to turn readily to them for the necessary details as to connections, voltages, capacities of transformers and such other information as he is in urgent need of. Some of the combinations of apparatus and connections which are most likely to arise, as well as others which are unusual, are presented herewith.

**Transformer Connections.** — The connections of standard line transformers are shown in Fig. 55 for convenient reference. Such transformers are made with two primary and two secondary coils, which permits their use on 2200-volt circuits, as shown in Fig. 55 (a), or 1100-volt circuits, as in Fig. 55 (b). Similarly the secondary may be connected for 110 volts to supply lighting or power on the two-wire

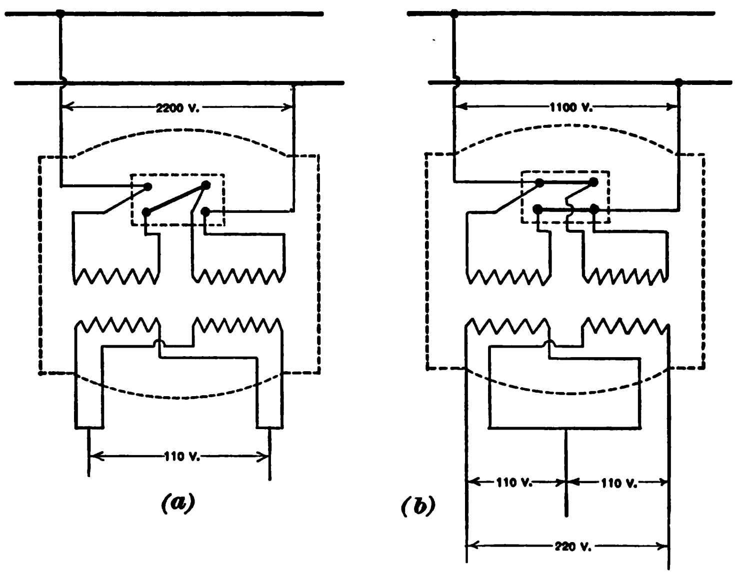


Fig. 55. Standard Transformer Connections.

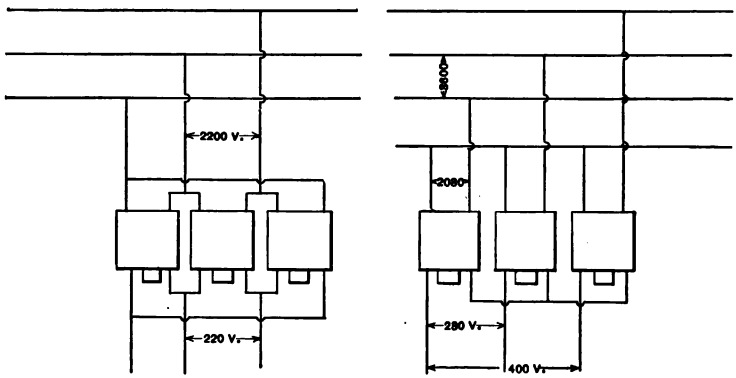
system, as in Fig. 55 (a), or for lighting or power on the three-wire Edison system at 110–220 volts, as in Fig. 55 (b).

Systems operating at approximately 2080 volts sometimes use a standard transformer having windings for 1040–2080 to 115–230 volts. Such transformers have a ratio of approximately 9 or 18 to 1.

The primary connections are changed from 2200 to 1100 by means of a connection block inside the transformer case.

The terminals of the secondary coils are brought outside the case in such proximity that they are readily put in parallel by joining the adjacent terminals. Likewise for 220-volt operation the two middle terminals are connected together, thus forming the neutral of the three-wire system. Connection blocks are not used on the secondary side because of the large current-carrying capacity required.

The connections for three-phase three-wire and four-wire systems are shown in Fig. 56. A simple way to remember




(c) (d)

Fig. 56. Standard Three-phase Transformer Connections.

the three-wire connection is to bear in mind that when all the transformers are connected in series in a closed circuit, a tap is made from each phase wire to the common point between any two transformers. This is familiarly known as the delta connection, so called because the triangle by which it is represented resembles the Greek letter delta.

The four-wire connection is easily reproduced by bearing in mind that all right-hand terminals go to the phase wires while all left-hand terminals go to the neutral, or *vice versa*. This connection is called the Y or star connection because of

its resemblance to those forms when represented in a polar diagram.

The secondary connection may be made either delta or Y in either system. The Y connection gives 1.73 times the voltage of the delta, and is therefore a useful device to resort to in giving 400-volt service from 230-volt transformers on a three-phase system. It may be taken advantage of in many other ways since it only requires the use of about 15 per cent additional pressure to make a ratio of 2 to 1.

In combining transmission systems it is often possible to use existing transformers by merely changing from delta to Y connection, or *vice versa*.

**Booster Transformers.** — Where it is necessary to raise or lower pressure by a fixed percentage, as is necessary when transformer ratios are not quite right or when line drop is excessive, this may be accomplished by a transformer used as a booster, that is, a transformer so connected that the primary main line is in series with its secondary. This raises the primary pressure by the amount of the secondary voltage, thus boosting the pressure of the circuit, as shown in Fig. 57.

For instance on a long, single-phase 2080-volt lighting branch which has so much load that the pressure drops more than the normal regulation of the feeder will care for, a 110-volt transformer inserted in the line as a booster will raise the primary pressure 110 volts. This raises the secondary pressure 5.5 volts on all the transformers beyond the booster. In the case of 440-volt service supplied by star-connected 230-volt transformers a 10 per cent booster in each phase raises the normal pressure of 230–400 volts to 253–440 volts.

Various other applications of the booster arise in every large distributing system, some of which are included in certain special cases considered hereinafter.

With the secondary connected in the reverse order the transformer becomes a choke, depressing the line pressure

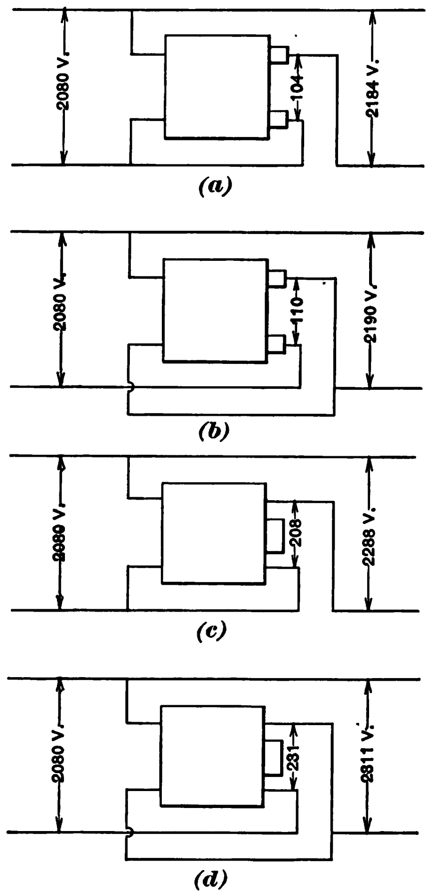



Fig. 57. Booster Transformer Connections.

instead of raising it. This is a useful device in some schemes of connection, where less pressure is desired.

The proper connection of the secondary for booster or choke must usually be determined by trial for any given

type of transformer, but once determined any transformer of the same type may be connected in a similar manner. The connections of Fig. 57 are those for the transformers of the principal makers.

The connections for a simple booster are as shown in Fig. 57 (a), the line pressure being raised from 2080 to 2184 volts, or 5 per cent. The connection in (b) is that for an augmented booster, in which the line pressure is raised from 2080 to 2190, because the primary of the booster is connected across the line on the far side, and the booster is boosted as well as the line. This gives an increase of 5.5 per cent in the line pressure.

Fig. 57 (c) shows 10 per cent simple booster and (d) an augmented 11.1 per cent booster.

The corresponding connections for a 5 per cent choke are shown in Fig. 58 (a), a 4.75 per cent choke in (b), a 10 per cent choke in (c) and a 9.1 per cent choke in (d).

It should be noted that the transformers used in these illustrations have an interchangeable 10 or 20 to 1 ratio of transformation, and that these percentages apply only to boosters having this ratio of transformation. If boosters having a ratio of 2080 to 115–230 are used the percentages are increased about 10 per cent. Figure 57 (a) becomes 5.5 per cent, (b) 6.05 per cent, (c) 11.1 per cent and (d) 12.2 per cent. Similarly the chokes in Fig. 58 (a) would be 5.5 per cent, (b) 5.24 per cent, (c) 11 per cent and (d) 10 per cent.

There are certain precautions which should be observed in the installation of boosters, to protect them from injury. The booster secondary is in series with the line, and current is drawn through its primary windings in proportion to the load on the line. If the primary of the booster is opened while the secondary is carrying the line current the magnetization of the transformer is greatly increased and the booster acts as a choke coil in the main circuit. This causes a large

drop of pressure in the booster, imposing upon its secondary windings a difference of potential of two to five times normal. The primary coils therefore generate a high pressure, and the insulation of a 2000-volt transformer may be subjected to a

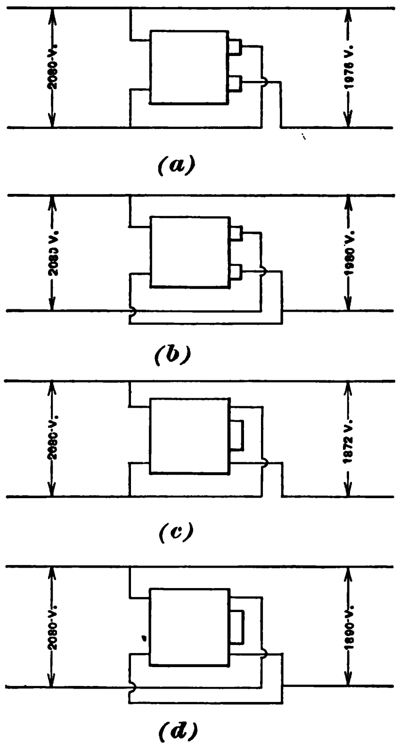



Fig. 58. Connections for Choking Transformers.

potential of 10,000 to 20,000 volts or more, depending upon the load carried by the main circuit at the time.

In case it is attempted to use a fuse in the primary the blowing of the fuse creates this condition and the arc holds across the terminals of the fuse block until it burns itself clear. It has often been observed that where boosters have

been " protected " by fuses in this way, the transformer has burned out shortly after the blowing of its primary fuses if not at the time.

**Booster Cut-Out.** — The preferable manner of connecting or disconnecting a booster is to open the main line before putting it in or out of circuit. This is sometimes undesirable, however, and if the service on the line cannot be interrupted, or if it is desired to switch the booster in or out at certain times, this may be accomplished by the use of a series arc cut-out, connected as shown in Fig. 59.

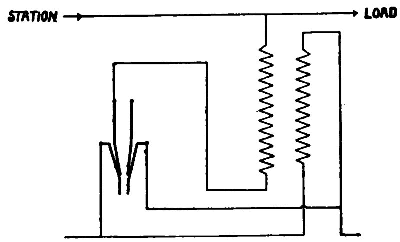


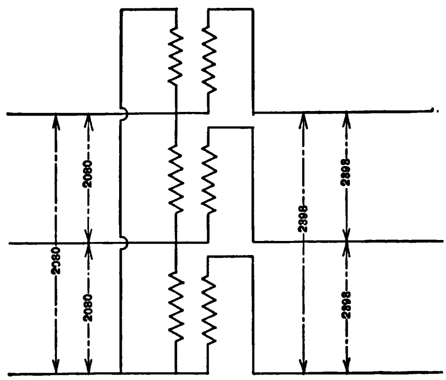

Fig. 59. Booster Cut-Out.

The operation of the cut-out simultaneously opens the primary and short-circuits the secondary of the booster. The switch must be of a type having a positive action, so that arcing will not damage its contacts at the moment the secondary is short-circuited. The arc cut-out must have sufficient carrying capacity to carry the main line current when the booster is shunted out, and standard series arc cut-outs should not be used where the line current is likely to be over 20 to 25 amperes.

When the augmented booster is used the terminals of the primary winding of the transformer which goes to the cut-out should be connected to that terminal of the cut-out which is shown as not being in use in Fig. 59.

**Boosters in Polyphase Systems.** — The connections for boosters in a two-phase system are similar to those shown in Fig. 57 for the single-phase system. Where three-wire two-phase feeders are used the boosters are looped into the outer wires and the pressure is taken from the common wire.

The use of boosters in a delta-connected three-phase system is not so simple as is the single-phase application. The booster is looped into the line wire and pressure is taken for its pri-




*(a)*

Fig. 60. Three-phase Three-wire Booster Connections.

mary coil from an adjoining phase wire, as in Fig. 60. The insertion in the line of the booster voltage, however, affects two phases, as shown diagrammatically in Fig. 61, which illustrates the effect of a 10 to 1 booster put into the " C " phase only. When boosting, the pressure from *A* to *C* is raised 110 volts, while *B* to *C* is raised 208 volts, the pressure coil of the booster being connected from *B* to *C*.

The effect of a booster in each phase is seen in Fig. 61 (c) in the larger dotted triangle, and the small triangle in the same figure shows the effect of a choke in each phase.

The boosting or choking effect when various booster transformer ratios are used in one, two or three phases is ex-

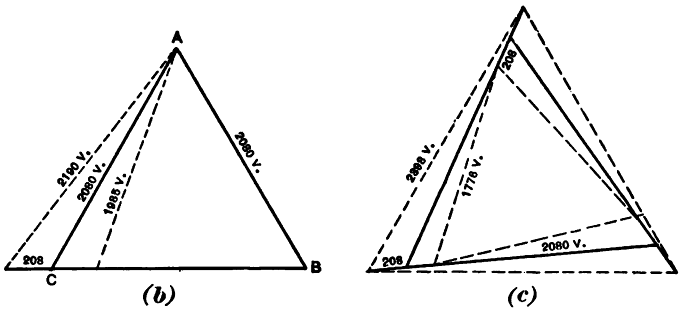



Fig. 61. Effect of Booster in Three-phase Circuit.

pressed in percentages of the primary voltage in the following table:

BOOSTING.

| Ratios. | 10 to 1. | | | 20 to 1. | | | 9 to 1. | | | 18 to 1. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Booster in | *A B* | *B C* | *C A* | *A B* | *B C* | *C A* | *A B* | *B C* | *C A* | *A B* | *B C* | *C A* |
| A phase.... | 10 | 0 | 5.3 | 5 | 0 | 2.65 | 11 | 0 | 5.8 | 5.5 | 0 | 2.9 |
| A and B.... | 15.3 | 10 | 5.3 | 7.65 | 5 | 2.65 | 16.8 | 5.5 | 5.8 | 8.4 | 2.75 | 2.9 |
| A, B and C.. | 15.3 | 15.3 | 15.3 | 7.65 | 7.65 | 7.65 | 16.8 | 16.8 | 16.8 | 8.4 | 8.4 | 8.4 |

CHOKING.

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A phase.... | 10 | 0 | 4.6 | 5 | 0 | 2.3 | 11 | 0 | 5.06 | 5.5 | 0 | 2.53 |
| A and B.... | 14.6 | 10 | 4.6 | 7.3 | 5 | 2.3 | 16.06 | 11 | 5.06 | 8.3 | 5.5 | 2.53 |
| A, B and C.. | 14.6 | 14.6 | 14.6 | 7.3 | 7.3 | 7.3 | 16.06 | 16.06 | 16.06 | 8.03 | 8.03 | 8.03 |

**Auto-transformers.**—The introduction of 110-volt tungsten or other high efficiency lamps into a 220 or 440 volt system in an industrial plant may be accomplished quite readily by the use of standard transformers used as auto-transformers. The connections in Fig. 62 are those for the use of two-wire 110-volt distribution on a 220-volt system, the load being

assumed at 20 amperes. The distribution of current in the windings is indicated by the figures and arrow heads. It will be seen that the transformer capacity required is equal to the load, when a standard transformer is used.

When the lighting is distributed on the three-wire 110–220-volt system, the transformer carries only the unbalance of current in the two sides of the system, as shown in Fig. 62 (b). In this case the unbalance is 5 amperes. The transformer carries $2\frac{1}{2}$ amperes at 220 volts, and need be only large

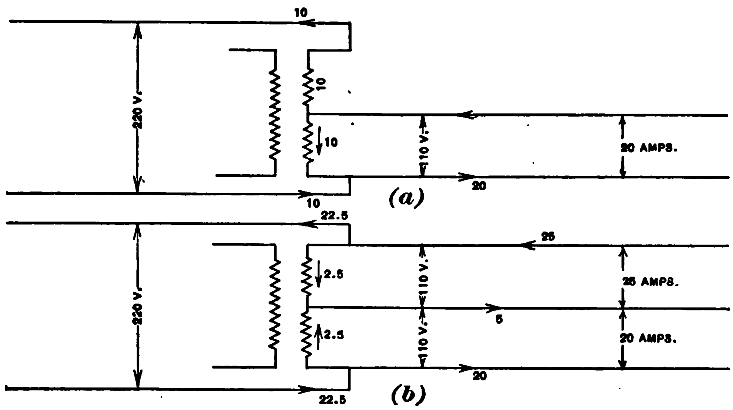



Fig. 62. Auto-transformer Connections.

enough to carry the largest unbalance which is likely to occur. The primary winding is left open and is not used.

In a 440-volt plant, where 110-volt lighting is desired, it may be secured from standard transformers, as in Fig. 63. This requires the use of two transformers in series on the 220-volt side and in parallel on the primary side. It is important that the primaries be in parallel, as the other transformer will act as a choke to the lighting current which must pass through it if they are left open, as in the 220-volt system.

The lighting distribution in a 440-volt system is preferably accomplished by the three-wire 110–220 volt system, as this requires transformers of capacity equal to the load, while two-wire 110-volt distribution requires that the transformer on the side on which the lights are connected have a capacity of 1.5 times the load, and the other one must carry half the load, making the total capacity twice the load.

It would be possible, of course, to run a five-wire system or two three-wire systems, and so reduce the transformer

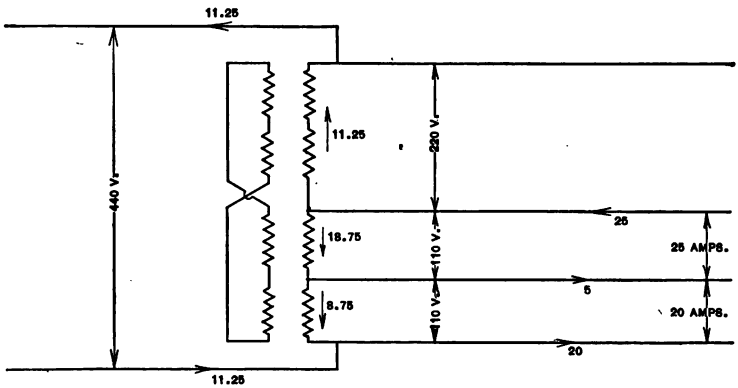



Fig. 63. 110–220 Volts from 440 Volts.

capacity to that of the unbalanced load, but this would not often justify the increased complication of the wiring which would be occasioned by such an arrangement.

Combinations may be made on the primary side of standard transformers in a manner similar to those above outlined for the purpose of securing intermediate or higher voltages from the supply system. 1040, 2600 or 3120 volts can be gotten from a 2080-volt system by the use of two transformers in series on the primary and in multiple on the secondary. These connections are shown in Fig. 64 (a), (b) and (c) respectively.

Various other combinations are possible by the use of more than two transformers, by which higher primary or lower secondary and other intermediate voltages may be derived.

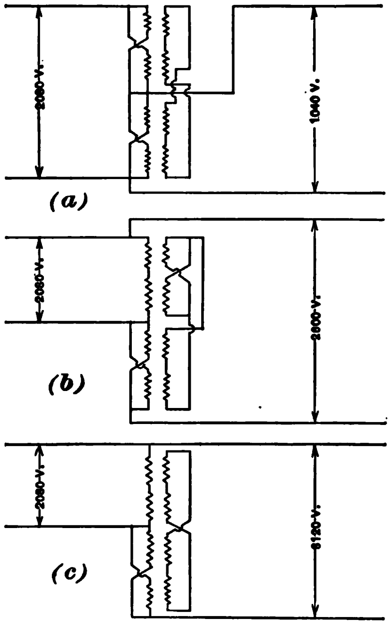



Fig. 64. 1040, 2600, and 3120 Volts from 2080 Volts.

**Applications to Special Cases.** — One application of the foregoing general principles serves to illustrate the value which such devices may have under certain conditions.

An installation consisting of a 300-K.W. 2080-volt three-phase motor was to be supplied with energy from a four-wire Y-connected system operated at about 2160 volts between phase and neutral, or 3740 between phases.

The only transformers available for the purpose were six 50-K.W. core-type transformers, with primary coils wound for 1040 or 2080, and secondary for 115 or 230 volts. By

connecting these transformers for 1040 volts on the primary and putting two in series from each phase to neutral, with secondaries in parallel, it was possible to take the motor circuit off at half the line pressure. The line pressure being but 3740, the additional amount required to get 4160 was secured by the use of a 9 to 1 booster in each phase.

The connections are shown in Fig. 65.

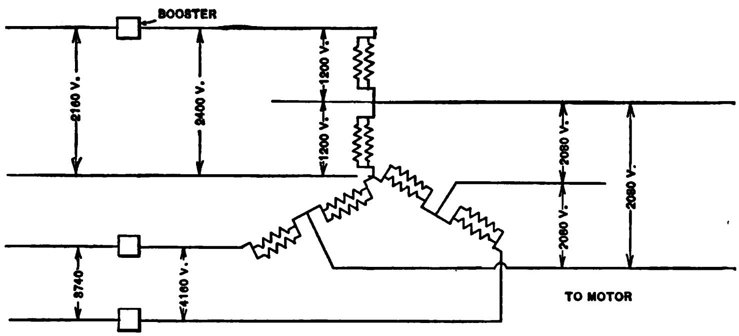



Fig. 65. 2080 Volts from Four-wire Three-phase System.

**Three-phase from Two Transformers.** — The expense incurred for transformers for small three-phase power service makes desirable in many cases the use of schemes of connection by which three-phase secondary pressure may be derived from two transformers. Two schemes of connections are possible for this purpose, one known as the open delta and the other as the T connection.

The open delta connection for a three-wire system is shown in Fig. 66 (a). This is merely an ordinary delta connection with one transformer left out. A simple rule by which this connection may be kept in mind is that both primary and secondary are connected in series as if it were a three-wire Edison system. The middle wire of the line goes to the middle point between the transformer on both primary and secondary.

In order to reverse the rotation the two outside wires must

be interchanged on the primary or either two of the three on the secondary side.

Fig. 66 (b) shows the open delta connection for a four-wire three-phase system. In this case the primary is connected

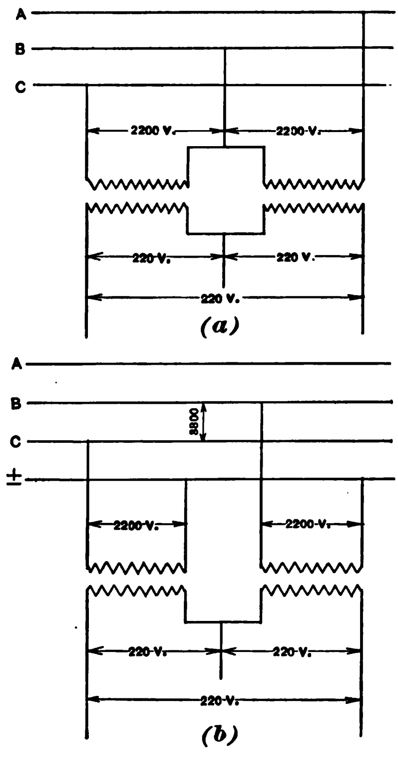



Fig. 66. Open Delta Secondary Connections.

so that both right or left hand terminals are taken from the neutral wire. The other two terminals are taken one each to any two phase wires. To reverse rotation on the primary side the phase wires should be interchanged. On the secondary side any two wires may be reversed.

The open delta connection requires 15.4 per cent more capacity in the transformer coils than three transformers. That is, if three 5-K.W. transformers are fully loaded by a given installation, they may be replaced by an open delta set of two $7\frac{1}{2}$-K.W. transformers, but the coils of the $7\frac{1}{2}$-K.W. units will be overloaded 15.4 per cent, at full load of 15 K.W., 100 per cent power factor.

This is evident from an example. Assume that in a three-transformer installation, the current in the secondary line is 17.3 amperes. This places a load of 10 amperes on the transformer secondary coils. At 200 volts this is 2 K.W. per transformer or 6 K.W. in all.

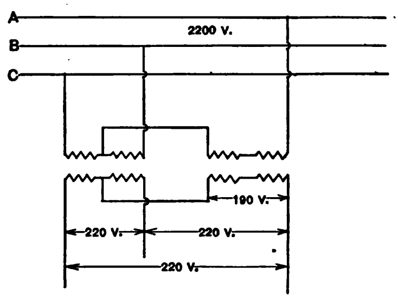



Fig. 67. T Connection, Three-phase.

If two 3-K.W. transformers were put in to replace the three 2-K.W. units, the capacity of the secondary coils would be 15 amperes. But with the open delta connection the current in the secondary coil is the same as the current in the line, and the 15-ampere winding must carry 17.3 amperes or 15.4 per cent overload.

With a three-wire three-phase system, power service may be given by the use of two transformers with the T connection on both primary and secondary, as shown in Fig. 67. The current overload is 15.4 per cent as with the open delta connection. This scheme cannot be used with standard 2200-

volt transformers on a four-wire system as the delta voltage is 3800. It is not possible to use this scheme with two transformers in series as the principle of operation requires that the current passing to the transformer at the left, in Fig. 67, from the other transformer, divide and pass each way from the midpoint. Thus the magnetic field of one balances the other. When two transformers are used across one phase the magnetic circuits are separate and the balancing reaction cannot take place. The connection to the middle point of the primary is not brought outside the case in standard transformers and it is therefore not often used.

This connection has a slight advantage over the open delta in the three-wire system, as the pressure across the right-hand transformer is but 86.6 per cent of the line voltage, which reduces the iron loss in this transformer about 15 per cent. The inherent regulation is also somewhat better.

**Two-phase Three-phase Transformation.** — The T connection is used in transforming from three-phase to two-phase or *vice versa*, as shown in Fig. 68.

It will be noted that one transformer must have a tap brought out so as to make the ratio of transformation on that unit from 1906 to 220 instead of 2200 to 220 as in the other unit. Standard lighting transformers are not usually equipped with an 86.6 per cent tap, but this connection may be quite closely approximated by the arrangement shown in Fig. 68 (b), when the transformation is made from two-phase to three-phase. Standard 10 to 1 transformers are used, one phase of the two-phase supply being choked by two transformers, one of which is connected for 9.0 per cent choke and the other for 4.5 per cent.

If the pressure desired for the motor service were 230 volts and the primary pressure were 2080 instead of 2200, the left-hand transformer in Fig. 68 (b) should have a 9 to 1

ratio. With a 10 to 1 as the other unit, the 9 per cent choking transformer could be dispensed with.

In transforming from three-phase three-wire to two-phase with standard transformers, the pressure on the right-hand transformer in Fig. 68 (a) must be raised by a booster. With a 10 to 1 transformer in the left-hand position, and a 9 to 1

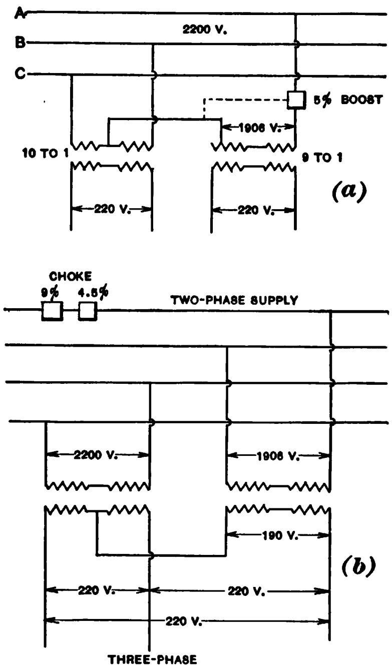


Fig. 68. Two Phase to Three Phase.

at the right, the pressure must be raised 5 per cent by a booster. The primary coil of the booster must be connected from A phase to the center of the T connection, as shown in Fig. 68 (a), in order to get the pressure of the booster in phase with the current in the right-hand transformer. If only 10 to 1 transformers are available, the right-hand transformer must be boosted 15 per cent instead of 5 per cent. If only

9 to 1 units are to be had, the left-hand transformer must be choked 10 per cent and the right-hand unit boosted 5 per cent, to give 220-volt two-phase service.

In deriving two-phase 440-volt supply two sets of transformers may be used, putting them in parallel on the three-phase side and in series on the two-phase side.

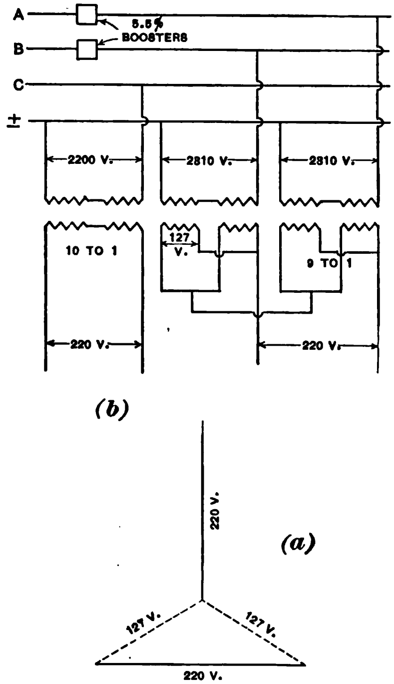



Fig. 69. Two-phase from Three-phase Four-wire Circuit.

It is impossible to derive 440-volt three-phase supply from a two-phase supply except with 440-volt transformers, since transformers will not operate in series on the T-connected side of such a combination.

In deriving two-phase 220-volt supply from a four-wire three-phase system with standard transformers it is necessary

to use three transformers connected as in Fig. 69. The unit at the left is a 10 to 1, connected from one phase to neutral. The two at the right are 9 to 1, connected with their secondary coils in multiple, and are arranged as two limbs of a Y, so that 127 volts are required at the transformer terminals to give 220 volts across the outer wires.

The three-phase system is unbalanced by this arrangement, since half the power is taken from one phase and the other half from the other two, making the balance in the proportions of 50, 25 and 25. The capacity of the transformers should also be in these ratios.

It is possible to use 10 to 1 transformers for all, but if this is done it is necessary to install 15 per cent boosters in each of the two phases supplying the right-hand transformer in Fig. 69. It is not possible to derive a four-wire three-phase system from a two-phase system with standard transformers.

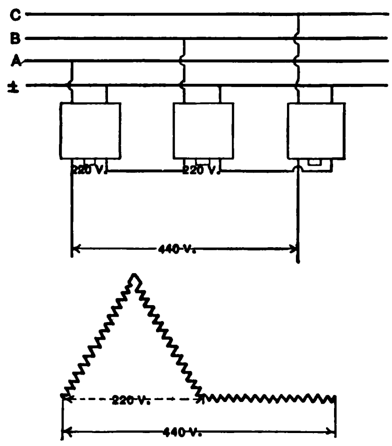



Fig. 70. Single-phase from Three-phase.

**Single-phase from Three-phase.** — In connection with electric welding and similar work requiring single-phase energy in amounts so large that the lighting service is interfered

with, it is desirable to distribute the load between the three phases. A scheme of connections which makes this possible is shown in Fig. 70, in which equal currents are drawn from the three phases to supply 440-volt single-phase energy. If 220-volt service were required the 110-volt connections of the transformers would be used. Each transformer must have capacity to carry half the current. Hence the total capacity must be 1.5 times the load. Where the location of the load is such that satisfactory lighting service can be given by distributing it between two phases instead of three, the ordinary star-connected secondary with 230–400 volts could be used with a 10 per cent booster in each phase to bring the pressure up to 440 volts. This arrangement requires only 15 per cent more capacity than the load.

# CHAPTER VII.

## PROTECTIVE APPARATUS.

**Historical.** — With the introduction of constant potential distribution for incandescent lighting, engineers were confronted with the necessity of providing some form of protection for generators and circuits which would save them from the effects of an abnormal flow of current when the circuit was accidentally crossed or short-circuited. This problem was fairly well solved for the conditions met in the early stages of the art, but it has reasserted itself with each increase in voltage and with the development of power stations of very large capacity. New and different solutions have been found for each case and the problem is still a live one.

In the early direct-current plants which were operated at about 110 volts the means selected for the protection of the apparatus consisted of devices to automatically cut off the supply of electricity when more current was drawn from the circuit than it could safely carry. The presence of an overload or short circuit was thus indicated in a way which required prompt action in the correction of the difficulty. It was found that wires of lead, tin and similar soft metals having a low melting point had a relatively high electrical resistance. This combination of physical properties suggested an automatic cut-out in the form of a fusible connection inserted in the circuit. These early circuits were therefore protected by the insertion of short pieces of soft wire, known as fuses, which were so arranged that the melted pieces could readily be replaced after conditions on the circuit had been restored to normal.

In another and more elaborate method a solenoid connected in series with the circuit was provided with plunger which tripped a spring and opened the switch in case of overload. This was called a circuit breaker.

The use of fuses for protection against overloads and short circuits in low-tension lighting systems became universal because of the simplicity and low cost of fuse renewals.

The blocks used for the support of fuses have been of various types. The earliest forms were of wood, these being followed by slate, marble and other stone and later by porcelain. In its primitive form the fuse consisted of a piece of lead wire secured under binding screws at each end. The uncertainty of this form of contact resulted in fuses blowing when they should not, and tips of copper suitably slotted to fit the binding screws were added. The use of wood was abandoned on account of risk of fire from the arc caused by the melting of the fuse. The use of slate and porcelain, while it eliminated the fire risk incident to the wood block, resulted in the chipping of the surface or the cracking of the block in case of the blowing of the fuse under short circuit with large amounts of power available. The insurance interests therefore forbade the use of porcelain for fuse blocks except where the fuse was enclosed, and required that where slate or marble was used, a suitable barrier be placed between the terminals, the purpose of this barrier being to hold the heat of the arc away from the surface of the block and to reduce the tendency of the arc to burn the contacts and binding screws. This barrier raises the fuse about an inch from the surface of the block and is quite effective.

**Enclosed Fuses.** — The danger of fire from the flash which occurs at the melting of the fuse when mounted on an open block led Edison, at an early date, to devise a form of enclosed fuse which could be easily renewed without the use of tools

and which could be refilled when blown at small expense. This fuse is the now very familiarly known Edison plug fuse. Originally glass was used as the insulating medium and the cover was made removable, but it is now made of porcelain instead of glass and the cover is attached so that it cannot be removed without the use of tools. This was found necessary on account of the tendency of covers to be left off. This form of fuse is one of the best and least expensive methods of protecting low-voltage branch circuits carrying loads of 1500 watts and under.

The protection of lines carrying larger loads was not found satisfactory with the plug type of fuse as the explosive force was too great when direct short circuits occurred. The copper-tipped fuse wire known as the link fuse serves this purpose economically, and is quite satisfactory for loads up to 50 kilowatts or more at low potentials. The link fuse, however, is unsafe unless enclosed in a fireproof box and mounted on a slate base with a suitable barrier between the terminals.

The danger arising from the use of open link fuses led to the development of a large variety of enclosed cartridge fuses. Most of these consist of a tube of fibrous material in which the fuse is mounted, and a filling around the tube of certain fire-resisting powders which absorb the vaporized metal when the fuse blows and smothers the arc. Connection is made at the ends by means of brass or copper terminals, copper being used on the fuses designed for currents of 60 amperes and upwards.

The use of glass and other nonporous substances in place of the fibrous tube has not been successful, as the pressure generated by the vaporization of the fuse metal within the tube must have means of escape, and the rigidity of the glass and similar solids is such that the tube is very apt to be exploded when the fuse blows on short circuit. The concealment of the fuse wire within the tube makes desirable some device

for indicating when the fuse has melted. This consists usually of a hole in the tube which permits a small portion of the arc to burn a paper covering, thus indicating at the surface that the fuse has melted.

The cost of installation and maintenance of cartridge fuses is necessarily several times greater than that of the link fuses. This has greatly retarded their adoption for low potential circuits, where the Edison plug and copper-tipped link fuses are most common. On 250 to 600 volt power circuits the use of cartridge fuses is quite general.

It is an unfortunate condition too frequently found that where the designing engineer has provided a safe and effective equipment of protective apparatus of the cartridge type, the operating engineer or manager, who knows little of the proper care of the apparatus, permits its effectiveness to be destroyed by the use of temporary devices designed to keep the circuit going but to postpone the expense of renewing the fuse. In many such cases it would be preferable to provide the less expensive installation of link fuses properly enclosed in boxes.

**Operation of Fuses.** — The operation of the fuse being dependent on the elevation of its temperature, the reliability of its performance on overloads depends upon the ease with which heat may be radiated. This is not so much of a factor in case of short circuit, as the temperature rise is so rapid that radiation has no appreciable effect.

Under normal load conditions the fuse may fail to carry its rated load because of insufficient opportunity for radiation or because of insufficient contact at its terminals, which adds to the heat instead of assisting in carrying it away. A fuse with a long length of wire between terminal clips will generally act at a lower current than one made of a short length, and a fuse mounted on lugs of liberal area will carry more than the same fuse connected to small lugs.

The action of enclosed fuses is in general somewhat more sensitive than open link fuses on account of the more restricted radiation of the enclosed fuse.

The time required to cause a 5-ampere fuse to operate at different loads is illustrated in the curve of Fig. 71. This curve is typical of the action of fuses of all sizes, the absolute values varying with different types and capacities.

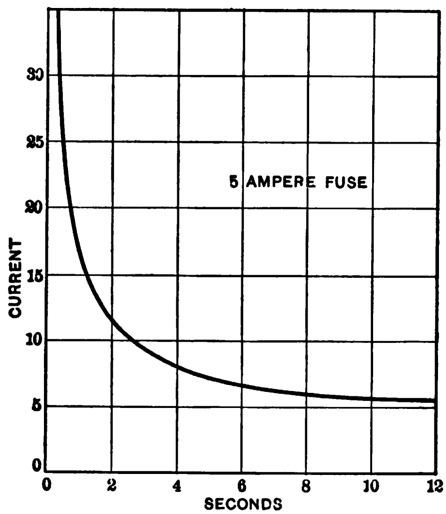



Fig. 71. Time Element of Fuse.

The law governing the operation of fuses was worked out by Preece in 1888. It may be stated with sufficient accuracy for general purposes in the form, Current $= a\sqrt{d^3}$, $d$ being the diameter of the wire expressed in inches. The value of the constant $a$ is different for each metal. For copper it is 10,244, for aluminum 7585, for lead 1379, for tin 1842 and for iron 3148.

For instance with a No. 10 B. & S. copper wire having a diameter of .102 inch, the fusing current is

$$C = 10{,}244 \times \sqrt{(.102)^3} = 334 \text{ amperes.}$$

The fusing currents for some of the smaller sizes of wire are as follows for copper and aluminum:

| Size Wire. | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\sqrt{(d)^3}$ | .046 | .0325 | .229 | .0162 | .0114 | .0081 | .0057 | .004 | .0028 | .002 |
| Fusing current copper | 472 | 334 | 235 | 166 | 117 | 83 | 58 | 41 | 29 | 20 |
| Fusing current aluminum | 349 | 246 | 174 | 123 | 86 | 61 | 43 | 30 | 21 | 15 |

**Methods of Protection.** — The design of a method of protection for a distributing system is necessarily a compromise between conflicting conditions. On the one hand the number and location of the fuses should be such that the area affected by the occurrence of trouble should be as small as possible, while on the other hand the fuse is a weak point in the circuit, prone to operate when it should not, and therefore should not be multiplied unnecessarily.

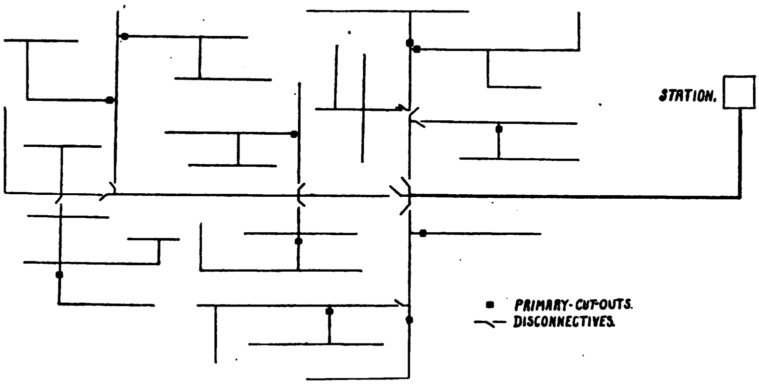



Fig. 72. Cut-Outs on Alternating-current Feeder.

In distributing electricity by overhead alternating-current lines over an area where the load is scattered so that mains are not interconnected, as shown in Fig. 72, experience has demonstrated that the arrangement of fuses indicated presents

a reasonably satisfactory compromise between the requirements of minimum area affected and minimum number of fuses.

The less important branches are isolated from the principal mains when trouble occurs on them without disturbing the remaining branches. In case of trouble on the trunk feeds the circuit is opened automatically at the station. If it has burned itself clear, as often happens, the circuit is closed and service is resumed very promptly. If it has not cleared itself the principal mains must be successively opened at the feeder end until the one in trouble is located. The remaining portions of the circuit are then put into service and the trouble is located on the affected main as soon as possible. It has been found undesirable to provide fuses at the points where the heavy mains leave the feeder, as they frequently blow when they should not, due to occasional extra heavy loads, deterioration of contacts or to trouble in some small branch which is severe enough to cause both branch and main fuses to blow simultaneously.

**Direct-current Systems.** — In overhead low-tension networks, using weatherproof insulated wire, the danger of short circuit is very slight if the lines are properly maintained, and it is therefore usual to omit fuses except at important points of supply so arranged that the occurrence of trouble will cut out reasonably small districts. Fuses at each junction are unnecessary, and involve more risk of trouble by blowing when they should not than of value in protecting the line against interruption. The work of repair is relatively quick, and it is therefore justifiable to risk larger areas than with low-tension underground lines.

In direct-current underground low-tension networks the work of sectionalizing must be done with the highest degree of refinement, owing to the density of the load, the length of

time required to make repairs and the general seriousness of an interruption when it occurs.

Trouble on a distributing main or service taken from it must be limited to the block in which it occurs, and if lines are carried on both sides of the street it must be restricted

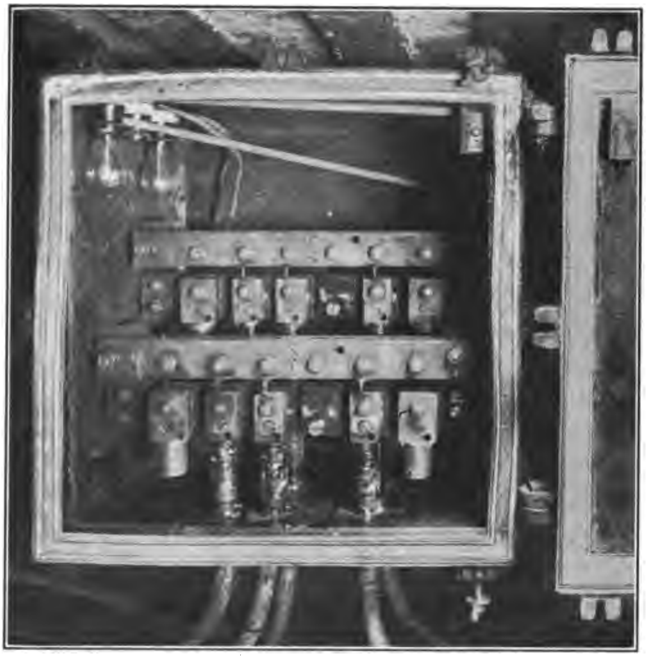


Fig. 73. Cable Junction Box, Manhole Type.

to one side of the street. Trouble on an underground main is usually of such a nature that considerable time is required to make repairs so that service may be resumed. For this reason it is usual to place fuses in underground mains at all points where they are connected into the system, so that in case of trouble the section affected will cut itself out.

In the early Edison systems junction boxes were provided

for underground work to protect the system from trouble on the mains. The clips in these boxes were equipped with copper-tipped fuses made of sheet metal of lead and tin, which produced a large amount of vapor when they blew under short circuit and were subject to a tendency to depreciation, which caused them to heat and blow unnecessarily at times. This difficulty was obviated later by the intro-

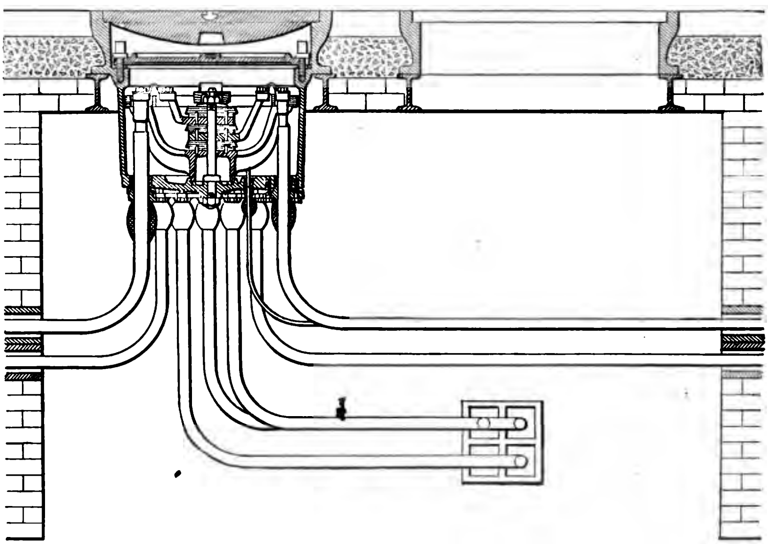


Fig. 74. Surface Type, Junction Box.

duction of sheet-copper fuses, such as those shown in Fig. 73, which are now in general use. This greatly reduced the weight of metal required and therefore the severity of the arc at the time of the blowing of a fuse. The section of the copper at the point where fusion takes place is designed to carry its normal rated load without undue temperature rise and to fuse at about twice its normal rating. Two types of junction boxes which have been used in connection with modern cable systems are shown in Figs. 73 and 74. The one

shown in Fig. 73, is installed on the wall of the manhole, while the other appears on the surface of the street.

The feeders are fused at the point where they feed the network, to protect the network against trouble on the feeder. It is not usual in large systems to provide fuses on the feeder at the station bus, as the operator on duty can open the switch and disconnect the feeder in case it is necessary. The likelihood of feeder fuses going out under emergency conditions when they should not, makes it preferable to omit protective devices of any kind at the switchboard, and depend on the operator to disconnect in case of trouble on a feeder. Such trouble is very rare in cable systems and increased reliability is secured by this practice.

**Alternating-current Networks.** — The protection of an alternating-current network of low-tension mains is carried out in a manner similar to that applied to direct-current systems when the network is fed by low-tension feeders from a substation, as the conditions are very similar as a rule.

When the network is fed by primary feeders and manhole transformers the situation is quite different, since an additional link is added in the chain which is a possible source of trouble, viz., the transformer. Where the load is so dense that the primary mains terminate within a radius of a block or two, no primary cable protection is advisable except the station circuit breaker and possibly a fuse at the primary side of each transformer. With the subway type of transformers in well-drained manholes the primary fuses may be safely omitted, as the risk of transformer burn-outs is less than that of interruptions due to primary fuses blowing or breaking down when no emergency exists. This would not apply where there are many scattered transformers as the location of a burn-out would require considerable time. Both

sides of the transformer should be connected to the network through junction boxes so that the unit can be easily cut off from the system if it burns out.

**Transformer Fuses.** — Line transformers should be provided with primary fuses of such size that they will not blow unnecessarily, and it is not advisable to attempt to protect transformers against ordinary overloads on this account. It is therefore usual to provide primary fuses having about twice the normal rated capacity of the transformer. The following table represents common practice on 2200-volt systems:

| K.W. capacity. | Size Fuse. | K.W. capacity. | Size fuse. |
|---|---|---|---|
| | Amperes. | | Amperes. |
| 1 | 3 | 15 | 15 |
| 2 | 3 | 20 | 15 |
| 3 | 3 | 25 | 20 |
| 4 | 3 | 30 | 20 |
| 5 | 5 | 40 | 30 |
| 7½ | 10 | 50 | 40 |
| 10 | 10 | ........... | ........... |

A type of fuse which has proven very satisfactory for transformers up to 20 K.W. is illustrated in Fig. 75. The

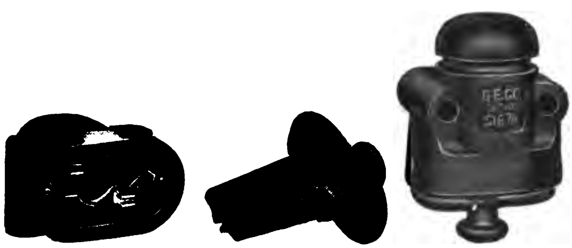


Fig. 75. Transformer Fuse Block.

removable porcelain plug carries contacts on which the fuse is mounted, and the heat formed by the melting of the arc produces an explosive action which blows out the arc. This

form of fuse is very satisfactory with aluminum as the fuse metal up to 15 or 20 amperes at 2200 volts. Above 15 amperes various types of fuse have been tried, but the amount of energy concentrated at the arc when the fuse melts is such that damage is done to the block, which in the course of a comparatively short time renders it useless. The cartridge fuse is effective up to 50 amperes when it can be kept dry enough to prevent the filler from absorbing moisture, but this is very difficult under average conditions.

**Primary Line Fuses.** — Various forms of fuses other than the cartridge type have been devised from time to time for use on primary lines and larger sizes of transformers. Most of these depend upon the explosive action of the arc to blow itself out.

In one form an aluminum fuse link is placed between two blocks of lignum vitæ, one of which has a hole above the point where the fuse melts. The arc is blown out through the opening where the link fuses. The lignum vitæ is slow to ignite and tough enough to resist the pressure. This form of block is fairly satisfactory on loads up to 50 amperes at 2200 volts.

Another on a similar plan consists of a fuse link carried between two blocks of asbestos board held firmly together by means of springs. When the fuse melts the metal is flattened out to a nonconducting condition and rapidly chilled by the close contact with the blocks. The arc is small and quickly suppressed. This type is shown in Fig. 76.

Another form is known as the bomb fuse. It is placed in a reinforced paper tube shaped like a small cannon. When the fuse blows inside the tube the vapor is expelled at one end as in the firing of a gun. The fuse is readily renewed by detaching the tube from its carrier.

Other forms of fuse depend upon the action of a spring which separates the terminals widely when the fuse melts. All of these forms are subject to injury on short circuit when a large amount of energy produces an arc which may hold and burn the terminals. Aluminum is used considerably because of the smaller amount of metal required than with

Fig. 76. Primary Line Fuse Block.

lead alloys, but it is subject to gradual deterioration when exposed to the weather continuously.

**Circuit Breakers.** — Under circumstances where automatic cut-outs operate at frequent intervals on circuits operating at high voltages or controlling loads of 100 K.W. and upwards, the circuit breaker possesses certain advantages over the fuse as a means of protection.

In general the use of circuit breakers is expensive in first cost but inexpensive in operation, while the use of fuses

requires considerable maintenance charge with a small first cost.

In mixed electric lighting and power systems the load is usually steady, and protective devices are not called upon to act except in case of line trouble. The use of fuses is therefore generally preferable in such systems except on feeder and transmission lines which carry large loads at high voltages where the use of fuses is not feasible.

On low-potential circuits the circuit breaker consists of a switch of a design suitable to control the maximum load of the circuit, with which is combined a coil connected in series with the circuit and so arranged that it will lift a movable core and release a spring-actuated mechanism which opens the switch. This plunger is designed to operate whenever the current exceeds a predetermined value.

Circuit breakers are commonly designed so that they may be adjusted to operate at any point between 80 and 150 per cent of their normal rated capacity. It has been found in practice that a magnetizing force of about 1000 ampere turns is ample for the operation of the tripping device.

In alternating-current systems the design of the circuit breaker is modified somewhat because of the fact that on such circuit breakers a series transformer may be installed at a convenient point in the main circuit and small wires carrying a few amperes may be led from the series transformer to the tripping coil of the circuit breaker. On circuits operating at 2200 volts and over the switch is commonly of a design which breaks in oil. The use of the series transformer on such circuits serves the double purpose of providing a small current for operating the tripping device and of insulating the mechanism from the high-potential circuits.

Circuit breakers are designed for two general classes of service in distribution systems: protection against overload or short circuit, and protection from the reversal of the flow of energy.

**Circuit-breaker Control.** — The operating mechanism of the circuit breaker is controlled by hand or electrically by solenoids.

In hand-operated breakers the power required to open the circuit is usually stored in springs during the act of closing. The overload or reverse-current trip releases the spring mechanism which in turn opens the breaker.

Fig. 77. Oil Circuit Breakers, Transmission Type.

In electrical operation the power for both closing and opening the circuit is supplied through solenoids or motors. The larger sizes and higher voltage breakers, such as those shown in Fig. 77, are usually controlled electrically on account of the power required and because of the greater facility of operation permissible with remote controlled switches. The latter feature is quite essential in large systems where the number of switches to be handled during an emergency de-

mands a system of control by which an operator may work rapidly and without great effort.

Direct current is usually available in stations and substations from the exciter system, and is often safeguarded by a storage battery, which assures control at all times. It is therefore usual to use direct current for the operation of

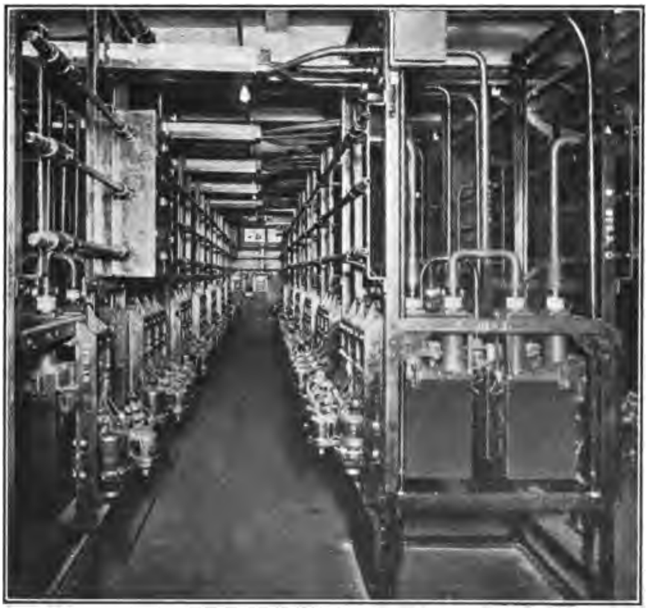


Fig. 78. Oil Circuit Breakers, Feeder Type.

electrically actuated breakers where possible. Circuit breakers usually are designed to open all poles of the line simultaneously in three-phase three-wire systems. In two-phase systems and in the four-wire three-phase system, single-pole or two-pole breakers are often used. A group of electrically controlled single-pole double-throw switches of the feeder type is shown in Fig. 78.

**Relays.** — With electrically controlled apparatus the protective device is really the relay which energizes the control circuit. This consists in general of an alternating-current solenoid energized by the main current transformer of the circuit, the plunger of which closes the direct-current circuit and energizes the mechanism of the circuit breaker as shown in Fig. 79.

In order to prevent the operation of the circuit breaker under momentary rushes of current, it is usual to design the

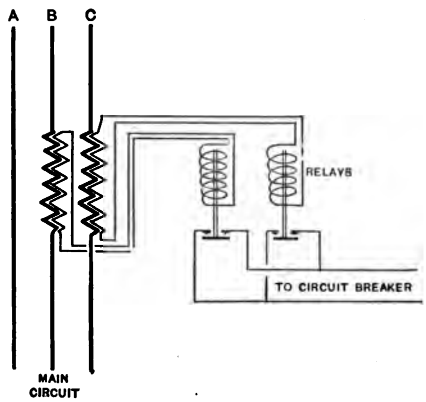



Fig. 79. Relay Connections.

relay for operation with an inverse time element. That is, with the relay set to operate at 100 amperes after 10 seconds, it will operate at about 300 amperes in five seconds and almost instantaneously at 1000 amperes. This characteristic results in prompt action in opening the circuit under short circuit, while reducing the liability of unnecessary interruption under minor disturbances.

This result is accomplished by damping devices of various kinds, such as dashpots and air bellows. The air bellows has proven the most satisfactory in view of its simplicity and reliability. Recent improvements made in the air release

valves have improved the action of the bellows type of relay on heavy overloads so that their operation on short circuits is more prompt and the damage reduced accordingly.

The arrangements of relays on a feeder or transmission line must be such that the occurrence of a short circuit between any two wires will open the breaker. On single-phase circuits one relay is sufficient to accomplish this. On two-phase three-wire systems carrying lighting and power it is desirable to provide separate relays and circuit breakers for the two outer wires so that only one phase is interrupted in case of trouble, which does not short-circuit both phases. This is also true of the four-wire two-phase system. In the three-phase three-wire system without grounded neutral the occurrence of a short circuit between any two wires interrupts service on all phases, and relays are required in two wires so that at least one will open the circuit in case of trouble on either phase. The circuit breaker is therefore a three-pole breaker.

In the four-wire three-phase system or in a three-wire three-phase system having the neutral point of the generator winding grounded, it is essential that relays be installed in each phase wire since the occurrence of a ground on either phase conductor results in a short circuit. In the four-wire system only the relays on the phases affected come into action. In case of a ground on one phase the circuit breaker on that phase opens without interrupting service on the other two phases.

When lines are operated in parallel in a large system the disturbance to the service is so widespread in case of a short circuit that it has become customary to operate transmission lines without interconnection. Thus where two or more lines run to a given substation they are not connected to the same high-tension bus. The protective equipment then consists of an overload relay on the line at the generating station and

reverse power relays on the converting units at the substation.

In case of a short circuit on a transmission line the oil breaker at the station opens automatically, shutting off the supply to the converting apparatus. The reverse power relay cuts off the supply from the opposite end and shuts down the unit or group which the line was carrying.

It is important that synchronous converters be further protected by speed-limit devices which are designed to operate the direct-current circuit breaker whenever the speed exceeds a safe maximum value. Such devices usually operate on the principle of centrifugal force, and being called upon to act rarely, should be tested out at intervals.

**Lightning Protection.** — When distributing lines are carried overhead they are susceptible to the influence of lightning. Being carried in a plane parallel to that of the earth's surface, every discharge among the clouds causes an abrupt change of potential on the wires, which must be given an opportunity to escape to earth in such a way as not to injure the insulation of the line or station apparatus.

The object of lightning arresters is, therefore, to permit the discharge of the lightning effects on the line without permitting the dynamo current to follow the arc thus established for more than a fraction of a second. This may be accomplished on potentials up to 300 volts by a short air gap of nonarcing metal with a fair degree of success. At 1100 volts or higher several gaps in series, together with a resistance sufficient to limit the current to about 10 amperes, are necessary.

As each wire of the circuit is affected, discharge gaps should be provided between each wire and ground. On ungrounded systems the dynamo current does not readily follow the static discharge, except when it occurs simultaneously on

two wires of opposite polarity. This, however, is likely to be the case when several flashes of lightning occur near the arresters.

In systems having one pole of the circuit grounded, every discharge from the ungrounded lines is followed by the dynamo current, as there is a fixed difference of potential between these wires and earth. Arresters on grounded systems are, therefore, subject to more severe requirements than those operating on ungrounded systems.

The problem of protection becomes much more complex as the voltage is increased, and the study of protective methods for transmission lines operating at 10,000 volts and upward is likely to continue for many years. It is quite too large a subject to be considered in this connection, and the discussion will therefore be restricted to distributing systems operating at 2000 to 4000 volts alternating current.

**Types of Arresters.** — The wide range of severity of lightning flashes makes it well-nigh impossible to design an arrester which will be of protective value during moderate flashes and which will also withstand the very severe flashes of a direct stroke at any point near the arrester.

The earlier types of arrester consisted of spark gaps in series with resistance rods, or a series of gaps without resistance. These were mounted in iron boxes and with 1100 volts single-phase circuits, with small power behind them, were reasonably satisfactory. At 2200 volts and with four-wire 2300–4000 volt systems with large station capacity, great trouble was experienced. The arc would often hold until the circuit opened automatically, and in wet weather the iron box would become charged and jump to the ground wire, destroying or crippling the arrester. This led to the use of wooden boxes which largely eliminated that class of

trouble though still leaving the arrester subject to damage at times.

Another form of arrester, which is illustrated in Fig. 80, embodies with gap and resistance a shunted solenoid so arranged that the plunger is raised by the passage of the dynamo current, thus opening the circuit.

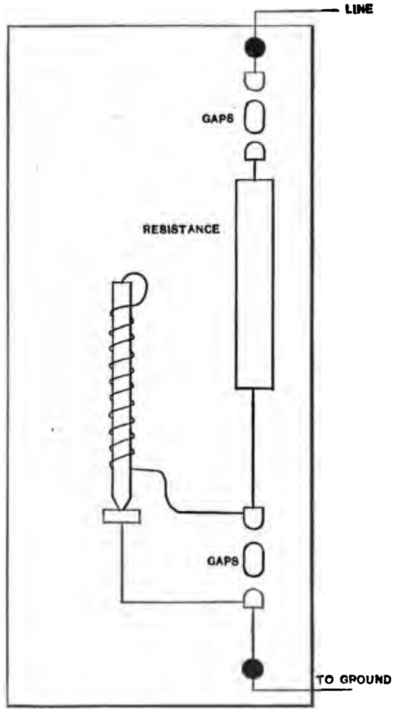



Fig. 80. Solenoid Type Lightning Arrester.

This type is subject to trouble, due to the puncture of the insulation of the solenoid winding which destroys the circuit-breaking feature and permits the dynamo current to flow uninterruptedly until the circuit opens elsewhere or the apparatus has burned itself clear.

However, both of these types have been used in great numbers in American practice with good results as far as the protection of the apparatus is concerned.

A modification of the spark gap and resistance type of arrester has been worked out for 2300-volt circuits with a

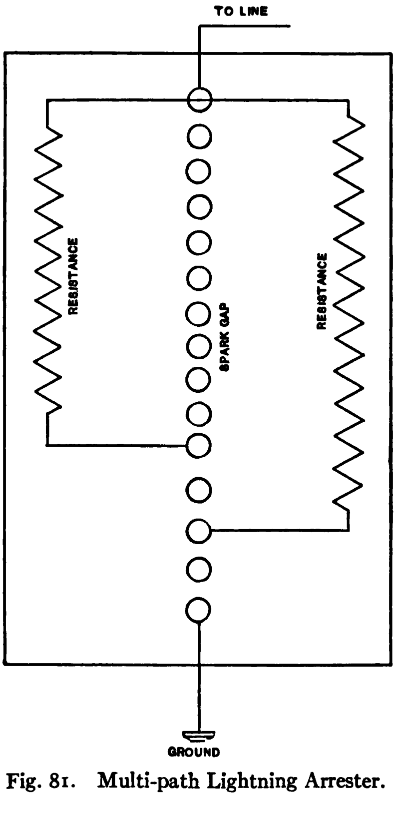



Fig. 81. Multi-path Lightning Arrester.

considerable degree of success. It is illustrated in Fig. 81 and consists of three paths of discharge, one of which has a resistance of about 100,000 ohms, another a resistance of about 300 ohms and another which consists of 13 or 14 gaps without resistance. The inductance and capacity of the parts

is such that very high frequency discharges pass over the 13 gaps, while lower frequency potential risers pass over the smaller number of gaps through one of the resistances.

The use of an aluminum cell as a lightning arrester has offered promising results because of its ability to choke the generator current upon the first alternation and thus prevent damage. It has been found especially valuable on transmission voltages where its expense is justified by the importance of the service. It is not suited for outdoor distribution work since it requires daily charging and supervision, cannot be left continuously in circuit and must be used in conjunction with horn gaps.

**Location of Arresters.** — The location of arresters on distributing circuits cannot be made subject to rigid rules. Many cases have occurred in transmission practice which indicate that severe lightning discharges do not travel along a line more than a few hundred feet on account of the inductance at the high frequency. It might, therefore, seem that arresters should be close enough together to come within the zone of any such stroke if complete protection is to be secured.

As a matter of experience, however, it has been found in some cases that where arresters are closer than 1500 feet the extra protection secured costs more than the loss in apparatus. It may, therefore, be considered as good practice to place sets of arresters at intervals of 1500 to 2000 feet or more.

Where transformers are larger and more numerous they should be closer than in the more scattered districts, and where underground cables are joined to overhead lines, arresters should be provided within 200 feet. Junction points are desirable locations for sets of arresters, as discharges may reach them from each branch of the circuit.

A suitable ground connection must be provided with as little inductance in the ground-wire arrangement as possible.

# CHAPTER VIII.

## OVERHEAD CONSTRUCTION.

### Pole Lines.

The use of overhead construction in the installation of distributing circuits is an economic and practical necessity in a large part of the territory supplied in every city. The investment per kilowatt of maximum load for overhead lines being from one-quarter to one-fifth of that required for underground construction, it is obvious that overhead construction must be used for as much of the distributing system as is feasible in order to keep the investment within profitable limits.

Overhead construction is, therefore, very generally found in the outlying parts of the larger cities and in all parts of smaller cities. It is not feasible to use overhead construction in congested business districts, as there is not proper room for the equipment in many cases, and its unsightly appearance makes it very objectionable to the general public. In most of the large cities the franchise under which the business is conducted requires underground construction in the congested districts. In many cases the objection to overhead lines may be greatly minimized by locating them in alleys, thus keeping the unsightly equipment out of sight and avoiding the defacement of fronts of buildings by service wires.

The use of overhead lines began with the earliest lighting systems which were installed for street lighting.

Poles and cross arms had been used for the support of overhead lines for many years in connection with telegraph work,

and it therefore only remained for the electric lighting engineers to make slight modifications in the spacing of the wires and in the type of insulator employed.

**Kinds of Poles.** — The most common form of overhead construction in American practice makes use of wooden poles with the wires on cross arms and pins. Iron poles are objectionable for general distribution work on account of the risk incurred by linemen in handling high-tension circuits alive while connecting transformers and doing other work. Iron poles are in use in some of the larger cities for street-lighting circuits which are not alive during the daylight hours and are so operated that it is not necessary to do any work on them while they are alive. The cost of iron poles is much more than that of wooden poles, which is a further disadvantage where the investment must be limited. Reënforced concrete poles have been introduced in some localities where wooden poles are exceptionally short-lived.

The woods which are best suited by natural growth for pole work in America are the Michigan cedar, Western cedar, chestnut, pine and cypress. Other woods are used, but only to a limited extent.

The Michigan cedar grows with a natural taper of about 1 inch in diameter to every 5 or 6 feet of length, except near the butt of the pole, where it flares out somewhat larger, making a very substantial and rigid pole. The sapwood, which is from 1 to 1½ inches thick, is soft enough to make the use of spurs very easy in climbing. The surface of the pole is comparatively free from knots and it grows fairly straight.

The Western cedar, which grows principally in Idaho, has a natural taper of about 1 inch in 8 to 10 feet of length. For the same size pole top the diameter of the butt is therefore small. The sapwood is about 1 inch thick and is a larger

proportion of the total cross-section at the ground line. The decay of the sapwood, which takes place first, therefore weakens these poles sooner than Michigan cedar and other poles of the same height and top diameter. The surface of Western cedar is smoother than that of the Michigan cedar and the poles are very straight and neat in appearance. The weight of the wood is light and is therefore easy to handle in erecting. It is preferable on important lines to use nothing smaller than 8-inch tops with these poles in order to get proper diameter at the ground line.

The chestnut pole is quite different in character from either of the cedar poles. The sapwood is thin and the specific gravity of the wood is high on account of its hard and densely formed fiber. This characteristic, together with the fact that the surface of the, pole is irregular and knotted, makes the work of shaving difficult and the appearance of the chestnut pole is not as good as that of cedar. The thin hard layer of sapwood makes the use of spurs difficult also. Chestnut is not as good an insulator as other kinds of wood, which tends to increase the difficulty of handling live circuits. It grows with a natural taper of about 1 inch in 6 or 8 feet.

Pine and cypress poles are more like cedar in their general characteristics of weight and strength. Their use is limited to sections of the country where the timber is native, as their life is comparatively short if moved to other climates and is not as long as cedar or chestnut in any event.

In general, the kind of pole used is governed by the proximity of the source of supply. In the South, pine, cypress and chestnut are commonly found. In the East and in the middle states, Michigan cedar and chestnut are used, while in the West, Western and Michigan cedars are general, except on the Pacific coast, where California redwood and some other native woods are used very generally.

**Strength of Poles.** — The strength of the poles selected for general distribution must be gauged by the importance of the lines they are to carry and by the local conditions which may affect the facilities for guying.

For special cases it is sometimes important to apply theoretical calculations as a check on the strength of poles which are to carry unusual strains, and the formulas for calculating stresses should be familiar to the designer of overhead distributing lines.

The strain acting on a pole tending to pull it over at the top is the most important one to be considered. This strain causes a tension in the fiber of the wood on one side of the pole and a compression on the opposite side. For a round pole the stress is

$$S = \frac{32\,PL}{3.14\,(d)^3},$$

in which $P$ is the equivalent pull at right angles in pounds at the distance $L$ in feet above ground and $d$ is the diameter in feet at the ground line, or $(d)^3 = \frac{32\,PL}{3.14\,S}$.

The strain $S$ at which any wood may safely be worked is not more than 10 to 12 per cent of its ultimate breaking strength as determined by tests of the timber in the form of poles. This high factor of safety is necessary because of the differences in the strength of different poles of the same kind of wood, the possibility of excessive strains being placed on poles in unusual emergencies, such as the burning off of all the wires of a span, and the fact that as the pole remains in service year after year, its strength at the ground line is lessened by decay, thus reducing the reserve available for an emergency.

It is found from tests that cedar, redwood and pine each have an ultimate breaking strength of about 7000 pounds per square inch when tested in the form of large timbers. Chest-

nut is slightly stronger, having a strength of 8000 pounds per square inch.

In using the foregoing formula the value of $S$ should therefore be taken at about one-tenth of these breaking strengths, or at 700 to 800 pounds.

If a self-sustained pole is to support a line which exerts a pull of 1000 pounds at a height of 30 feet above the ground, what should be its diameter at the ground line to safely carry the strain?

Let $S$ be $\frac{1}{10}$ of 8000 = 800, $P$ = 1000, $L$ = 360 inches.

$$(d)^3 = \frac{32 \times 1000 \times 360}{3.14 \times 800} = 4584,$$

from which $d$ = 16.5 inches. This would call for the use of a pole 35 feet long with a butt 16 inches at the ground line and a top diameter of 8 to 9 inches in Michigan cedar, or 10 to 12 inches in Western cedar.

Conditions similar to those assumed above are frequent in city practice where streets or alleys jog or where turns are made at right angles which cannot be supported by a guy, as in the case of the line branching from Main Street to the alley east of Third Street in Fig. 82.

**Wind Pressure.** — The design of pole lines to withstand wind pressure in a lateral direction must be considered where sections of line are exposed. Fortunately the average city pole-line distribution is so protected by buildings and trees that it is not subject to the full force of windstorms. In exposed sections and on transmission lines supplying suburban substations, the force of the wind may be felt at times very greatly, and lines should be built accordingly. The force of a windstorm is most apt to be an element of danger when it is exerted at right angles to the direction of a line, since there are normally no strains in this direction and no

system of support is provided except for protection from storms.

The pressure of the wind blowing against a surface normal to its direction was found by Langley in a series of experiments made in 1888 to be $p = .0036 (v)^2$, in which $v$ is the velocity of wind in miles per hour and $p$ is the pounds per square foot. From this it is evident that $p$ is 20 pounds per square foot when the wind blows at 75 miles per hour, or 5 pounds at 37.5 miles per hour.

The force exerted upon poles and wires varies with the angle at which the wind strikes them, being a maximum at 90 degrees. In figuring the area of surface exposed, allowance must be made for the fact that the surfaces are cylindrical. A cylindrical surface presents but two-thirds as much surface to the wind as a flat surface of a width equal to the diameter of the cylinder. A 40-foot pole having a top diameter of 7 inches and a butt at the ground line of 14 inches, set 6 feet in the ground, has an average diameter of 10.5 inches. The length above the ground being 34 feet, the equivalent area of pole surface exposed is $\frac{34 \times 10.5 \times 2}{12 \times 3}$ = 19.8 square feet. The diameter of a No. 6 wire with triple-braid weatherproof insulation is about .3 inch. With 120-foot spans the area exposed per wire per span is

$$\frac{120 \times 12 \times .3 \times 2}{144 \times 3} = 2 \text{ square feet.}$$

As the force due to the action of the wind on the wires is exerted near the top of the pole it is more effective than the forces acting along the pole at various heights, due to the pressure of the wind on the pole.

Calculations made for a 40-foot pole indicate that the strain imposed by the action of the wind on the pole itself is approximately equal to that caused by five weatherproof

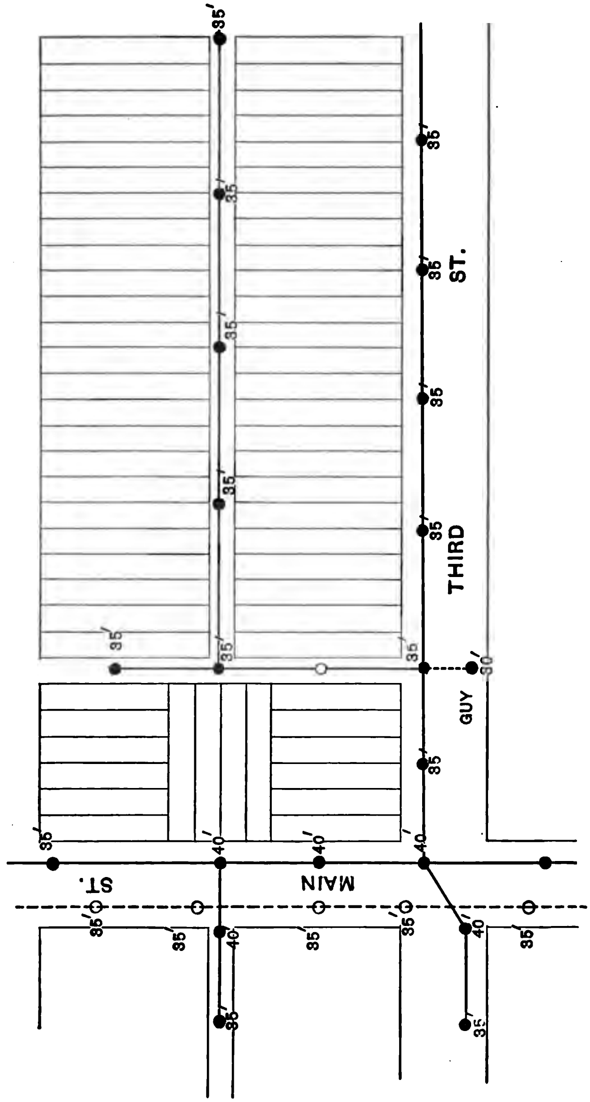



Fig. 82. Method of Placing Poles.

wires of No. 6 B. & S. gauge. At a velocity of 52 miles an hour, the wind pressure being about 10 pounds per square foot, the force exerted on each No. 6 wire of a 120-foot span is $10 \times 2 = 20$ pounds. The force exerted on the pole due to its own surface is equivalent to about 100 pounds applied near the top. The total force on the pole at such a wind velocity with 30 wires would therefore be $600 + 100 = 700$ pounds. Or at a wind velocity of 75 miles and a force of 20 pounds the strain on the pole would be 1400 pounds.

High velocities are attained for short intervals in nearly all parts of North America, and it is therefore advisable to provide protection for such sections of line as are exposed to the force of winds, if they carry more than 10 or 12 wires. This protection is sometimes difficult to provide when lines are on public highways. It may consist of struts on the side opposite that from which winds are expected, or guys secured to anchors on the windward side.

**Selection of Poles.** — In the selection of poles for distributing lines such as those shown in Fig. 82, the poles at corners and turns must be such that they will hold the wires taut for a reasonable period after they are strung. The intermediate poles should have sufficient strength to support the weight of any ordinary size of transformer and not pull too much out of line if more service drops are taken off on one side than on the other.

Service drops average about 75 feet in length and may be allowed to hang with considerably more deflection than the main line wires. The unbalanced sidewise pull on a pole, therefore, does not usually exceed 300 pounds. With the services attached at a height of 30 feet, the size of the pole at the ground line should be

$$(d)^3 = \frac{32 \times 300 \times 360}{3.14 \times 800} = 1375, \text{ or } d = 11 \text{ inches.}$$

This corresponds to a cedar pole with a $5\frac{1}{2}$ to 6 inch top. However, the use of poles of this size is not permissible in sections where more than one or two service drops are likely to be taken from any pole, as the bending of so slender a pole under the strain pulls the line out of shape. It is therefore

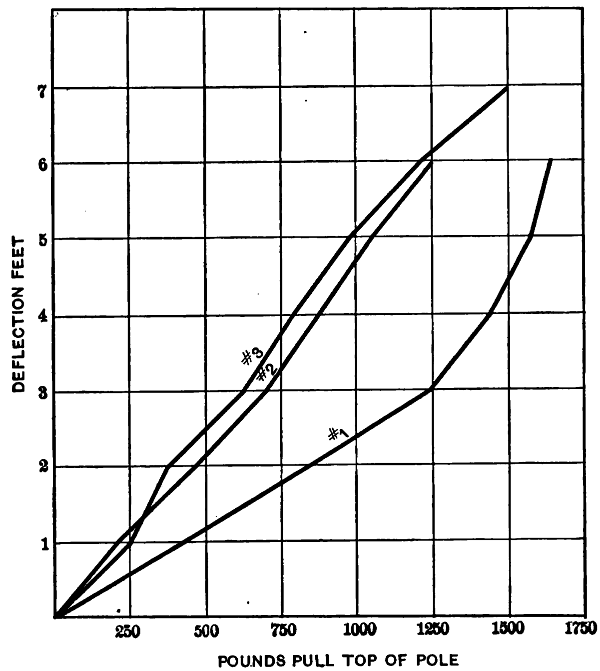



Fig. 83. Bending Test of Cedar Poles.

usual to select 7-inch-top poles for all important distributing lines, 6-inch poles being used only in the very scattered districts.

The curves shown in Fig. 83 are the results of a test on cedar poles to determine their rigidity and strength. Curve No. 1 shows the average of several Western cedar poles,

35 feet long, 23 inches in circumference at the top and 37 inches at the ground line. Curves No. 2 and No. 3 are for Michigan cedar poles of approximately the same top dimensions. The test was made by securing the pole at the butt and applying a load at the top at right angles to the length of the pole. The end of the curve indicates the point at which rupture occurred in each case, No. 1 being at 1600 pounds, No. 2 at 1200 and No. 3 at 1500. It will be noted that the pull required to deflect the pole 1.5 feet is much less with the Michigan cedar than with the Western cedar, the latter being the stiffer throughout the test.

A deflection of more than one foot becomes noticeable in the appearance of a line and tends to place additional strain upon the pole. A strain of more than 250 to 300 pounds should therefore be balanced by a guy attachment or should be supported by a pole of heavier cross-section if guying is impracticable.

The height of the poles selected for distribution purposes must be governed by the requirements of clearance over local obstructions and by the number of cross arms to be carried on the poles. The presence of other pole lines, of trees, elevated railroad structures and buildings, requires the use of higher poles than would otherwise be necessary in some cases. Clearance over trees is especially troublesome in residence sections where trimming will not be permitted. In some cases it is better to go above and in other cases below the trees with the wire. Trouble is apt to be experienced, due to the growth of the trees, when wires are carried above, and it is difficult to clear limbs and branches below.

In general it is not desirable to use poles less than 30 feet long where primary lines are carried, and in built-up sections a minimum size of 35 feet is preferable. Poles of from 60 to 70 feet or more are sometimes required to give proper clearance and cross-arm space. Where joint construction with another

company is used it is not customary to use poles smaller than 35 feet, except for guy stubs.

It is not necessary to maintain an entire line of high poles merely to preserve the general level where a part of the line must be elevated to clear obstructions. The use of high poles is to be avoided wherever possible, in view of the cost of installation, the increased danger of failure in time of storm and the difficulty of handling transformers and service connections.

**Location of Poles.** — The length of spans is affected by a number of considerations. Poles should be close enough to keep the deflection of the span within safe limits and to provide a sufficient number of points at which service drops may be taken off, and yet must be so spaced that the block or section of thoroughfare will be divided into approximately equal span lengths. The spans near self-supported corner poles should be from 75 to 90 feet if possible, in order to relieve the strain on the corner pole. The poles should be placed at lot lines to avoid interference with the rights of abutting property owners and to save expense of moving in case new buildings are erected. The average city lot being about 25 feet in width, there are usually some spans 125 and others 100 feet or less in length. It is not advisable to exceed 125 feet in span lengths, as the number of services per pole and their average length is increased, thus placing greater strain on individual poles.

**Pole Painting.** — The good appearance of poles in public thoroughfares has much to do with creating a friendly feeling on the part of the public toward a public-utility corporation. It is therefore considered good policy to carefully shave all poles, to remove knots and bark and then give them two coats of paint. A dark green color is very commonly used

because of its unobtrusive nature and its harmony with foliage in residence districts. A priming coat may be given the pole in the yard, the second coat being preferably applied after the work on it has been completed.

**Pole Steps.** — All poles which are likely to be climbed to any extent, such as transformer poles, junction poles, poles carrying fuse boxes, other accessories or services, should be provided with pole steps. This expense is justified in view of the serious injury done the surface of the pole by the climbing spurs of linemen in the course of time. Pole steps are commonly spaced from 30 to 32 inches apart, alternately on opposite sides of the pole.

**Gains.** — The pole should be cut for the reception of the cross arms before it is erected. These incisions, called gains, should be about ½ inch deep and of the necessary width to receive the arm. The distance between centers must be sufficient to give clearance for buck arms and service drops and allow a safe working space for linemen. The space usually allowed is therefore 22 to 24 inches, preferably 24 inches between gains.

**Pole Setting.** — The depth at which poles are set must be such that the strains in any direction will not pull the pole over or out of line. Experience has proven that the following practice is conservative for poles in a straight line:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Size pole........ | **30** | **35** | **40** | **45** | **50** | **55** | **60** | **70** |
| Depth........... | 5′ | 5.5′ | 6′ | 6.5′ | 6.5′ | 7′ | 7′ | 7.5′ |

Corner poles should be set about 6 inches deeper than the above.

The character of the soil and the diameter of the butt of the pole affect these figures in some cases.

For instance, a Western cedar pole with a small butt set in a sandy soil or swampy soil will be much more likely to pull over than a Michigan cedar of the same height with a heavy butt, and rather more depth should be provided for it. In rocky soil where bowlders may be tamped about the pole they need not be set so deep.

The pole should be turned so as to bring the bend of the pole into the line and should be set erect except at corners, where a slight rake may be given in a direction opposite the strain. Several tampers should be employed to one shoveler in filling the hole, as the thoroughness with which tamping is done while the hole is being filled is an important factor in the stability of the pole. Water may be used to settle the earth where the soil is dry and light.

Where swampy soil is encountered, or in quicksand, the sinking of the hole must be accomplished by the use of a sand barrel. This consists of a sheet-iron cylinder about 30 inches in diameter and three feet long, which is separable into two parts lengthwise. After the hole has been started the barrel is set into it, and as the earth is removed it slips down, preventing the sides of the hole from caving in. After the pole has been erected the barrel is withdrawn and removed by loosening the separable attachments.

In case the earth filling does not give sufficient stability in such soil this may often be secured by the use of a concrete filling from 6 to 10 inches thick at the base of the pole and at the ground line. This has the effect of increasing the bearing surface of the pole and will often prevent the gradual pulling out of line which takes place in such localities.

At corners, bends and dead ends which cannot be properly guyed for any reason, the pole carrying the strain must be self-sustained. This may be done by the use of a concrete filling as described above or by the use of timbers secured to the pole as shown in Fig. 84. Poles having top diameters of

8 to 10 inches should be used for this class of work. The timber method requires the excavation of a rather large hole, but it provides an ample bearing surface and is usually less expensive than the concrete method. The timbers should be about four feet long and 8 to 10 inches in width. They may be of 3-inch plank or a section of an old pole. The upper timber should be at least 6 inches below the surface in order to preserve the timber.

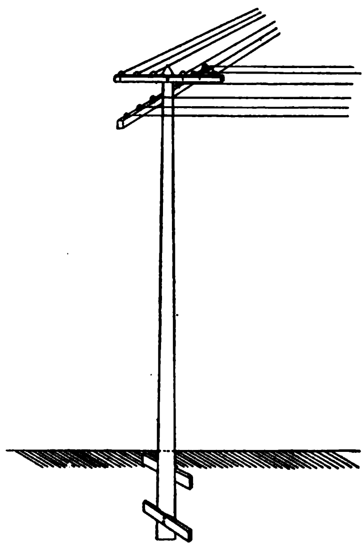


Fig. 84. Timber Supports for Corner Pole.

**Guying.** — At all points where the direction of a line changes the tension of the wire must be supported by suitable guying equipment of such strength and design as will insure the permanent solidity of the poles supported.

In suburban work it is sometimes possible to support a corner pole by a brace consisting of a shorter pole placed against it at a proper angle to support the strain. This method though effective requires some space, and is more unsightly than a guy wire. Guy wires are secured at the ground in various ways, depending upon the room available and the clearance required overhead.

Where there is nothing to prevent the guy wire being brought down to the ground near the poles the guy cable may be secured to an anchor as shown in Fig. 85. The anchor is made of a timber such as a piece of a pole 4 feet long, or it

may be a patent anchor of some form. The use of the timber requires a large excavation, while most of the patent anchors are driven or screwed in without digging a hole. The timber method is therefore somewhat more expensive in cases where the nature of the soil is such as to permit the installation of the patent anchors.

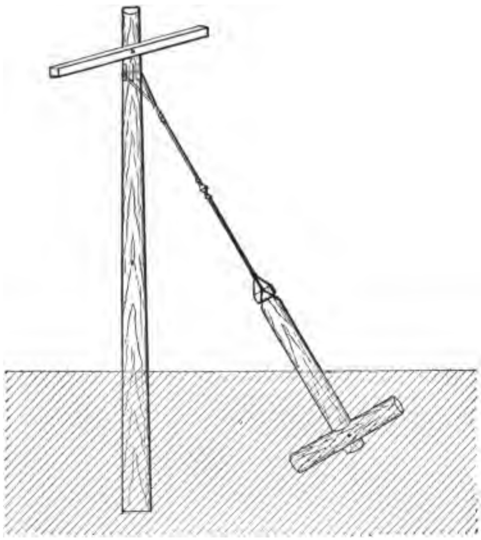


Fig. 85. Anchor Guy.

Where the soil is rocky or where obstructions exist, excavation is necessary and the timber method is likely to be preferable.

Where trees of sufficient size to hold lines without swaying are available they may be used sometimes as anchors. Other fixed objects, such as large rocks and buildings, may also be used in special cases. The location of corner poles on public thoroughfares is often such that guys cannot be run directly to anchors without interfering with traffic. Under such circumstances the guy must be run to a pole known as a

stub, where it is attached at such a height as to permit free passage under it. It is usually required that guys over roadways clear the crown of the road about 25 feet, while those crossing pathways should clear at least 12 feet.

This class of attachment is illustrated in Fig. 86.

The stub is sometimes made self-supporting where the use of an anchor is not practicable or where the height of the stub is not over 15 feet.

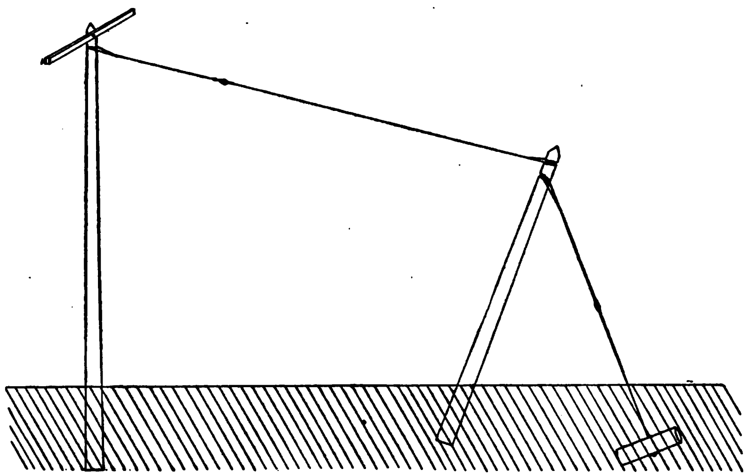


Fig. 86. Anchored Stub Guy.

On lines which carry three or more cross arms it is important to attach guys on the pole at two points so that the strain will be distributed and the pole will not be gradually bent out of shape.

Where side arm or alley arm construction is used it is necessary to support the cross arms as well as the pole by means of guys attached to eyebolts in the arm.

At heavy corners which are guyed to stubs or anchors and at self-sustained corners the head guy may be used to good advantage. It is run from the base of the corner pole to

the upper part of each adjacent pole in the line. If the line wires are well secured at the poles next to the corner the tension in the two corner spans may be reduced, thus relieving the strain on the corner pole materially.

In straightaway lines the head guy is useful in limiting the extent of damage in case all lines burn off or several poles go over in a wind storm. The head guys on long lines are placed at intervals of about 20 poles. Similarly where a long span exists which is likely to become crossed and burn open, head guys should be maintained at each side to support the line each way in such an emergency.

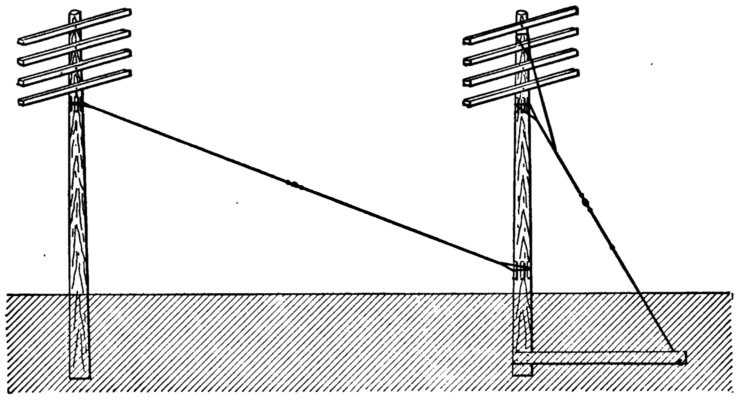


Fig. 87. Head Guy at Terminal Poles.

A typical use of the head guy on a terminal pole is illustrated in Fig. 87.

Generally speaking the head guy is a useful means of securing reserve or auxiliary guying for the other forms of guys. Terminal poles, corner poles and jogs in the line may often be head-guyed to advantage.

**Guy Cables.** — Steel wire or cable is generally employed for guying purposes because of its high tensile strength and cheapness. It should always be galvanized, since the value of

the guy is largely dependent upon its durability and reliability, and plain steel wire is subject to rapid corrosion which steadily weakens it. The stiffness of steel wire is such that it is very difficult to bend it in securing the ends in sizes above No. 8 B.W.G. without impairing its strength. It is therefore used most generally in the stranded forms for guying purposes.

Side arms may be guyed by a single galvanized steel wire of No. 6 B.W.G., but stranded cable is preferable for all line work. Such cable is made in sizes varying by $\frac{1}{16}$ inch in diameter from $\frac{1}{4}$ inch up. The strength of steel wire being about 80,000 pounds per square inch, the ultimate breaking strength of $\frac{1}{4}$-inch cable is about 4000 pounds; $\frac{5}{16}$-inch, 6000 pounds; $\frac{3}{8}$-inch, 8000 pounds; and $\frac{1}{2}$-inch, 15,000 pounds.

**Calculation of Size of Guy Cable.** — The pull on a pole due to the tension of the wires having been calculated from the size of the wires, their deflection and span lengths, the tension on the guy wire is equal to the sum of the tension of all the line wires multiplied by the length of the guy wire and divided by the horizontal distance from the pole to the point where the guy wire is attached to the anchor or stub.

Having calculated the tension in any case the size of guy cables should be such that the strain will be from $\frac{1}{4}$ to $\frac{1}{5}$ the ultimate breaking strength of the cable.

For instance, with a line carrying 18 wires at a tension of 150 pounds each, supported by a guy cable 40 feet long, with the anchor attachment 30 feet back from the pole, what size of guy cable should be used? The total line wire tension is 2700 pounds, and the guy cable tension is therefore $\frac{2700 \times 40}{30}$ = 3600 pounds. This is approximately one-quarter the ultimate breaking strength of $\frac{1}{2}$-inch stranded cable.

In case the anchor were but 12 feet back from the pole, the cable would be about 36 feet long, and the tension on the guy would be $\frac{2700 \times 36}{12} = 8100$ pounds.

This would necessitate the use of two $\frac{1}{2}$-inch cables attached to the anchor, and a head guy of $\frac{3}{8}$-inch or $\frac{1}{2}$-inch cable to the first pole back from the terminal pole. The head guy, acting at a more favorable angle, could be adjusted to carry nearly half the strain if turnbuckles were provided in the guy to permit this. An anchor should not be placed nearer to a pole than one-quarter the height of the guy attachment on the pole. In general, the $\frac{1}{4}$-inch size of cable is ample for the smaller strains, while the $\frac{3}{8}$-inch size is standard for corner poles and similar work where the strain of the ordinary two-arm distribution line is to be supported. Heavy feeder lines, such as those used in the foregoing example, require special consideration.

**Attachment of Guys.**—In making attachment of a guy cable to a pole or stub it is preferably given two turns about the pole and the end brought back and well secured. The smaller sizes may be secured at the ends by wrapping, but the larger sizes are preferably fastened by means of clamps bolted on. When an anchor having an eye at the upper end is used the cable should be protected by a thimble to avoid too sharp a bend at the point where all the strain is carried.

**Strain Insulators.** — The proximity of guy cables to primary wires affords opportunity for leakage in wet weather and renders them subject to accidental crosses with live conductors at times. It is therefore important that every guy cable be equipped with strain insulators and that they be attached to stubs not less than 8 feet from the ground. These precautions are advisable for the protection of the public and of

linemen, whose safety is endangered by the presence of grounded guy cables near live wires on which they are working. It is therefore customary to keep guy cables above ground as much as possible and to sectionalize them by the


Fig. 88. Guy Strain Insulator.

use of one or two strain insulators of the type shown in Fig. 88. The strain insulators should be put in about six feet from each end.

The guying equipment should be installed before the wire is strung, so that when the tension is applied the corner poles may be pulled up to their normal position.

Fig. 89. Porcelain Guy Insulator.

In supporting the strain of high-tension wires it has become customary to employ porcelain strain insulators having large leakage surfaces designed to withstand transmission voltages. One of this type is illustrated in Fig. 89.

With heavy low-tension feeders the same result is secured by attaching a strain insulator of the type shown in Fig. 90


Fig. 90. 600-Volt Strain Insulator.

directly to the conductor and using a separate guy wire for each conductor back to a guy pole.

# CHAPTER IX.

## OVERHEAD CONSTRUCTION.

### LINES AND ACCESSORIES.

**Cross Arms.** — In the selection of wood for cross arms for distribution work the physical characteristics of the wood must be carefully considered. Longleaf Southern pine and Oregon fir are the best woods because of their straight grain, high tensile strength of fiber and durability. The chief cause of deterioration in cross arms is the alternate action of the sun and rain, which tends to open up cracks on the upper side, allowing water to soak into the wood and create conditions which are favorable to processes of decay. It is therefore important that the top surface of the cross arms be rounded off so that the water will run off easily.

The cross-section should be of such shape and area that the arm will bear the weight of a lineman in addition to that of the wires without danger of breaking. This demands a good factor of safety to provide for proper strength after the arm has become weakened by partial decay. Experience has proven that a cross-section $3\frac{1}{4}$ inches wide by $4\frac{1}{4}$ inches high is ample for the average requirements of distributing lines. In handling transformers of 20 K.W. and larger it is desirable to provide special arms of a large cross-section on account of the weight to be supported.

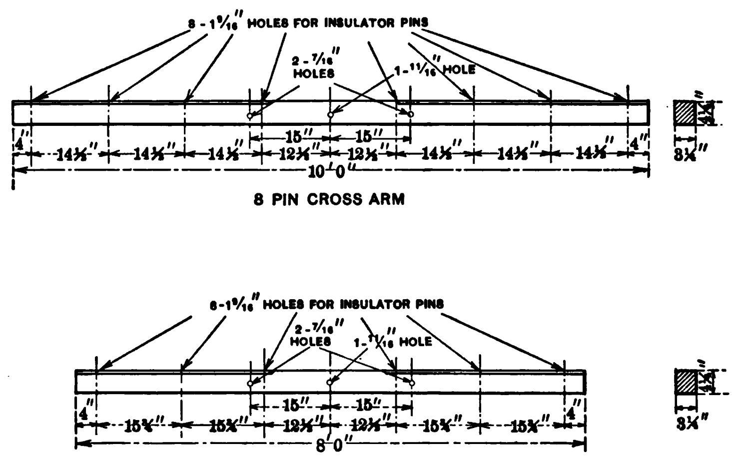
The appearance of a distributing line is best if a uniform length of cross arm is used. In suburban districts main lines are commonly of six- or eight-pin arms with four-pin arms on the distributing lines.

In city work where both light and power secondaries must

frequently be carried on the same arm, it is found necessary to use six-pin arms for distributing lines with eight-pin arms on main lines.

Where lines are occupied jointly with other companies it is desirable that arms of approximately equal length be used by both companies.

The appearance of lines is improved by a quiet color of paint, and the same color is sometimes used on both poles and cross arms.




6 PIN CROSS ARM

Fig. 91. Dimensions of Cross Arms.

The spacing of pins should be suited to the voltage of distribution, should provide a safe working space for linemen and should take into account the average sag of the wires. Under the usual working conditions of distributing lines it is not safe to attempt to use spacings less than 12 inches, and 14 to 16 inches between centers is more commonly found. Increased spacing results in arms of excessive length where eight-pin arms are required. In general, the wider spacings are common on four-pin arms and the narrower on eight-pin

arms. With longer spans more space should be provided, the spacings being at least two-thirds of the deflection of the wires. The spacing of pins next to the pole must be such that sufficient room is left for linemen to get up through the lower wires safely to work on the upper arms, at least 24 inches being required between pole pins and 30 inches being preferable. The dimensions and spacings of standard cross arms are shown in Fig. 91. Specially wide spacing is desirable between the pole pins of arms used on corner poles, as

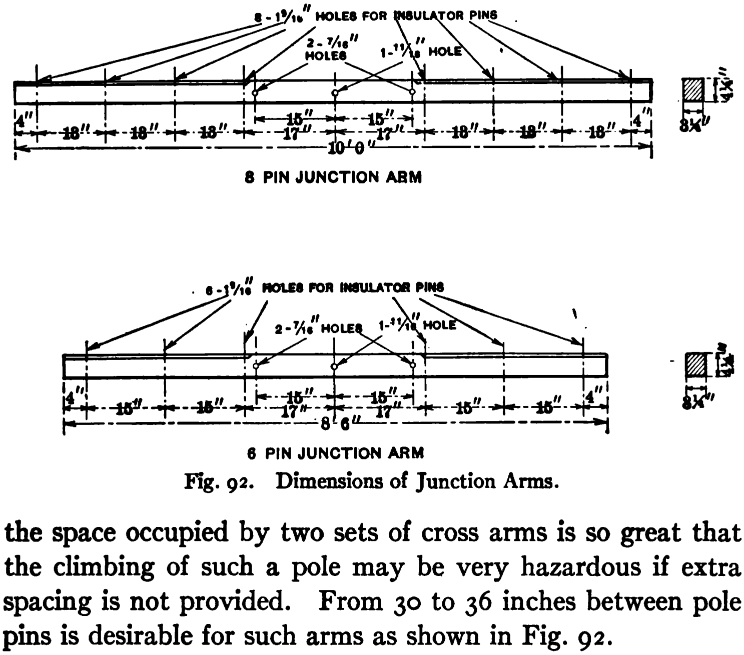



Fig. 92. Dimensions of Junction Arms.

the space occupied by two sets of cross arms is so great that the climbing of such a pole may be very hazardous if extra spacing is not provided. From 30 to 36 inches between pole pins is desirable for such arms as shown in Fig. 92.

These dimensions are typical of standard practice, though there may be small variations from them in different localities.

**Side Arms.** — In cities where the system of alleys is general these thoroughfares are used wherever possible for distributing lines. The narrowness of the roadway is such that

the poles must be set close to the property lines, and the presence of buildings at intervals also makes it necessary to keep the cross arms from overhanging the property. This necessitates the use of side arms, or alley arms as they are more commonly known, as shown in Fig. 93. The unbalanced strain on the pole caused by such construction is not serious and is readily compensated for by setting the pole with a slight rake toward the property line. The weight of the

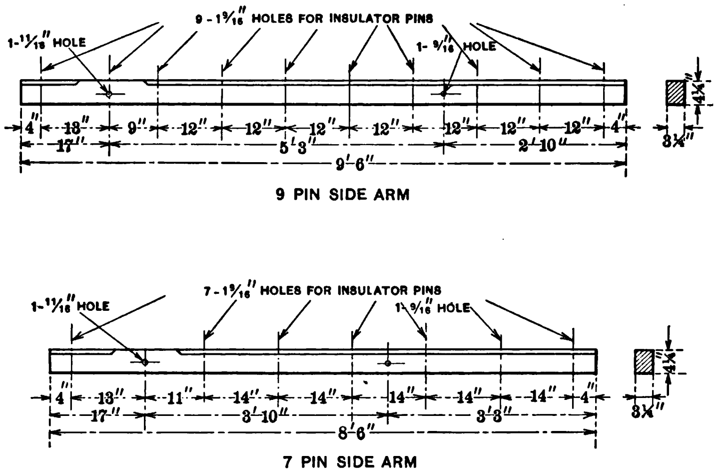



Fig. 93. Dimensions of Side Arms.

equipment of cross arms and wires then brings the pole up straight.

**Double Arming.** — At corners, terminals and other points where any unusual strain of extra weight is to be supported, the poles should be fitted with a double arm equipment so that the strain will be carried by more than one support. In turning corners on a single pole the double arming of both sets of arms makes the pole difficult of access to linemen and specially wide arms, shown in Fig. 92, should be used. It is

preferable, in case there are more than two cross arms on the lines, to double-arm the first pole away from the corner in each direction and support the line by means of head guys as shown in Fig. 94.

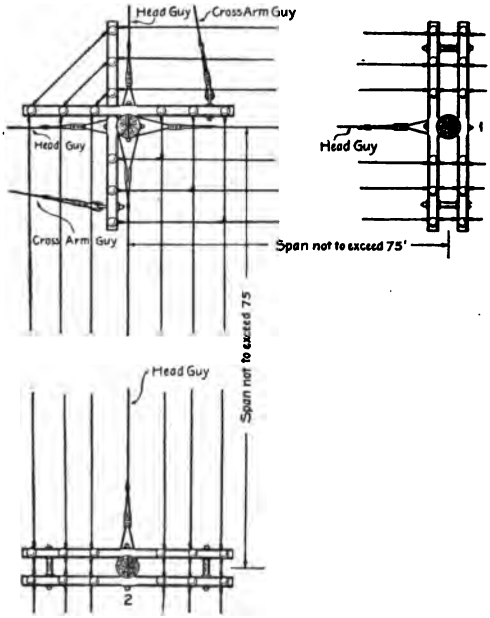



Fig. 94. Double Cross Arms at Corners.

**Arm Bolts.** — Arms may be fastened to the pole by bolts or lag screws. The use of bolts is preferable in the long run, as the fastening of the arm becomes insecure in the course of time, due to decay of the pole around the threads of the lag screw. When a bolt is used it is fitted with a nut and washer on both ends to give a firm and durable seat for the nut. The bolt should be $\frac{5}{8}$ inch in diameter and from 12 to 16 inches long, depending upon the diameter of the pole. The side of the pole on which the cross arm is attached is generally known as the face of the pole, the opposite side being

the back of the pole. Where lag screws are used the arms should be attached to the poles of a line so that the poles will stand face to face and back to back in alternate spans. This will prevent the cross arms being torn off from the poles by the strain of the wires if all wires burn off. This is a wise precaution with bolts also, but not so important as with lag screws.

**Arm Braces.** — In order to hold the cross arm firmly in a horizontal position, braces must be provided. These are usually of strap iron about $\frac{1}{4}$ inch by 1 inch by 26 inches to

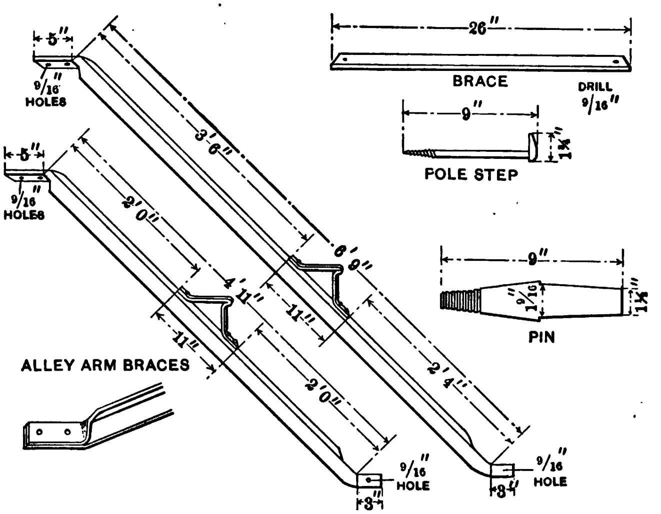



Fig. 95. Pole Line Fittings.

30 inches long. The brace is placed at an angle of about 45 degrees with the pole and is attached by means of lag screws to the pole and by stove bolts through the cross arms.

Side arms must be supported at a point farther out from the pole than center arms and it is therefore usual to use a brace of angle iron such as that shown in Fig. 95. This is rigid enough to bear the weight of a lineman on the step

while working on wires at the outer end of the arm. This brace is used only on the lower arm where there are several arms on a pole.

The upper arms must be supported by braces of $\frac{1}{4}$ inch by 1 inch by 26 inches strap iron run vertically from the outer end of the angle iron brace.

**Pins.** — Pins of wood are preferred for distribution work on account of their strength, durability, low cost and insulating qualities. Locust, elm, oak and other similar woods are common, but locust is superior to all in its strength and durability. Tests made on pins of the sizes shown in Fig. 95 gave an ultimate breaking strength of about 1200 pounds for oak, 1400 pounds for elm and 1600 pounds for locust. These figures represent the pull in pounds applied on a deep-groove double-petticoat insulator mounted in its normal position on the pin, and therefore indicate the breaking strength of the pin under working conditions. A factor of safety of 4 to 6 is advisable, and care must be used in selecting pins free from knots and dry rot and having straight grain. Where wires of No. 0 and smaller are dead-ended or carried around a corner it is customary to distribute the strain between two pins by using double-arm construction. With heavier cables it is not desirable to attempt to support the strain by a pin, but it is usual in such cases to insert a strain insulator in the line near the pole and take the strain more directly on the guy cable.

Pins should be coated with white lead before being put into the pin holes and should then be secured by a sixpenny galvanized nail. It is usually better economy to fill all pin holes with pins in the shop before the arms are sent out for use. Iron pins are commonly used for transmission lines where the size of the insulator necessitates a pin so long that wooden pins of the ordinary type are not adequate.

**Insulators.** — The most common type of insulator in American distribution practice is that known as the deep-groove double-petticoat glass insulator, shown in Fig. 96. The dimensions of this insulator are sufficient to carry circuits operating at potentials up to 500 volts safely with standard wooden pins. The groove will carry any size of weatherproof wire up to 4/0. The line wire is secured to the insulator by a tie wire laid in the groove and twisted around the line wire several times at each side of the insulator. The point of support is relatively low and the side strain on the pin is therefore reduced to a minimum.

Fig. 96. 2300-Volt Insulator.

Fig. 97. 6600-Volt Insulator.

The double petticoat is ample protection from leakage of electricity during stormy weather.

The glass insulator is usually less expensive than porcelain insulators designed for the same class of service, and is equally rugged mechanically.

On transmission circuits which may operate at potentials above 5000 volts, the porcelain insulator is preferable even though more expensive. The type shown in Fig. 97 is generally used for 6600 volts and that in Fig. 98 for 10,000 to 15,000 volts.

Fig. 98. 13,200-Volt Insulator.

**Wire.** — The wire used for overhead distribution work should be of annealed copper and covered with three fibrous braids impregnated with weatherproof compounds.

The size of wires is in general determined by the conditions of load, distance, etc., but in overhead work the mechanical strength must be adequate and it is therefore not safe to use wire smaller than No. 6 for primary lines. It is also common practice to extend this rule to low-tension lines, though No. 8 is sometimes used for short secondary lines. No. 8 and No. 10 are used for service drops to small consumers quite generally.

**Wire Stringing.** — In stringing wire it is usual to draw several wires by a rope and a team of horses over the cross arms on several spans of line. When in place one end is secured and tension applied to the wires separately by the use of block and tackle. When the tension has been correctly adjusted linemen stationed at several points apply the tie wires, thus securing the line to the insulators. The remaining wires are similarly drawn up, care being taken to get the tension on all wires about the same. The tension varies with the size of the wire and with the deflection which is considered permissible. It should be made sufficient to prevent too much sag in the spans and yet must not be so great as to unduly strain the wire and the guying equipment which supports it.

**Calculation of Tension and Sag.** — The theoretical curve formed by a wire supported under tension as in pole work is known as a catenary. The equation of this curve is based on the assumption that the wire is inextensible and perfectly flexible. This is, of course, not strictly true of insulated copper wire, and it is therefore found sufficiently accurate for all practical purposes to use the approximate formula of Rankine and others as follows: $T = \frac{(L)^2 w}{8S}$, in which $T$ is the wire tension in pounds, $L$ is the length of the span in feet, $w$ is the weight of one foot of conductor and insulation, and $S$ is the sag or deflection in feet.

To illustrate, assume a No. 6 weatherproof wire carried on poles 100 feet apart, with a sag of 1 foot; what is the tension on the wire? The weight of one foot of No. 6 wire being about 0.112 pound, $T = \frac{100 \times 100 \times .112}{8 \times 1} = 140$ pounds. If the spans were 141 feet, the strain would be doubled, and at 200 feet they would have to be quadrupled in order to keep

the deflection one foot. If the tension is the same on several spans, the deflection will be different in each span. In practical work this is usually the case, as the tension is usually the same throughout any section of line unless special provisions are made for guying certain spans of unusual length so as to increase the tension.

With a deflection of one foot in a 100-foot span and a spacing of 14 inches between wires, there is very little danger of wires swinging together in a high wind, as they swing in synchronism. With a sag of more than two feet in a 141-foot span, however, there is more danger of wires touching, as they are loose enough to allow them to swing out of synchronism in a gusty wind. The deflection for any span when the tension is known is found by interchanging $T$ and $S$ in the foregoing formula so that it reads $S = \frac{(L)^2 w}{8 T}\cdot$ In the case of a 4/0 wire in a 141-foot span under 1025 pounds tension

$$S = \frac{141 \times 141 \times .82}{8 \times 1025} = 2 \text{ feet.}$$

The maximum tension in a line is limited by the strength of the wire and its supports on the one hand and by the requirements of clearance on the other hand. The ultimate breaking strength of annealed copper wire is about 34,000 pounds per square inch. The working strain should not be over one-quarter of this on the smaller sizes, as the swinging of wire in the wind tends to weaken it at its supports, and if pulled up too tight it stretches, increasing the sag and diminishing its cross-section.

For No. 6 wire, which has an area of .0206 square inch, the ultimate breaking strength is about 700 pounds. The safe working strain is therefore about 175 pounds, which gives a 14-inch sag in a 125-foot span. The safe working strength of 4/0 wire, which has an area of .1662 square inch, is found in a

similar way to be 1400 pounds, which gives about 15 inches sag in a 125-foot span.

With hard-drawn wire the ultimate tensile strength is about 60,000 pounds. The surface of such wire is left in the hardened condition in which it comes from the wire-drawing dies, which gives it greater strength and stiffness. The wire, however, must not be scratched or kinked in handling, as any injury to the surface reduces the strength of the wire at that point to the strength of annealed wire. The same is, of course, true if it is heated for soldering. Hard-drawn wire is therefore not adapted to general distribution work where taps must be made with soldered connections at frequent intervals. For transmission lines and series arc circuits it has advantages which are generally recognized and made use of. It is used for telephone work exclusively, in order to permit the use of a small conductor with strength sufficient to support the tension of the span. The sag and tension of weatherproof and bare, hard-drawn wire are presented in the following table for various sizes of wire.

ANNEALED WEATHERPROOF WIRE, 100-FOOT SPAN.

| B. & S. G. | 10 | 8 | 6 | 4 | 2 | 1 | 0 | 2/0 | 3/0 | 4/0 |
|---|---|---|---|---|---|---|---|---|---|---|
| *T* at 1 ft. sag | 62 | 92 | 140 | 204 | 318 | 390 | 486 | 607 | 767 | 942 |
| *S* at 100 lbs. tension | .62 | .92 | 1.40 | 2.04 | 3.18 | 3.9 | 4.86 | 6.07 | 7.67 | 9.42 |
| Weight wire per ft. | 50 | 74 | 112 | 163 | 254 | 312 | 388 | 486 | 614 | 754 |
| Breaking stress | 283 | 440 | 700 | 1114 | 1772 | 2234 | 2818 | 3553 | 4480 | 5650 |

HARD-DRAWN BARE WIRE, 100-FOOT SPAN.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *T* at 1 ft. sag | 39.3 | 62 | 99 | 157 | 161 | 202 | 400 | 505 | 636 | 800 |
| *S* at 100 lbs. tension | .393 | .62 | .99 | 1.57 | 1.61 | 2.02 | 4.0 | 5.05 | 6.36 | .80 |
| Weight wire per ft. | 31.4 | 50 | 79.5 | 126 | 201 | 253 | 320 | 403 | 508 | 640 |
| Breaking stress | 500 | 778 | 1237 | 1967 | 3127 | 3943 | 4973 | 6271 | 7907 | 9971 |

The tension at any other deflection, or the sag at any other tension, or either sag or tension in any other length

of span, may be readily found from the above figures as follows:

The tension at any other deflection is $T' = \frac{T}{S}$, in which $S$ is the deflection in feet at which the tension is desired and $T$ is the value in the above table in pounds.

For illustration, what is the tension in a 100-foot span of No. 0 weatherproof wire at a deflection of 2 feet?

$$T' = \frac{T}{S} = \frac{486}{2} = 243 \text{ pounds.}$$

Similarly the sag at any other tension is $S' = \frac{S \times 100}{T}$, in which $T$ is the assumed tension and $S$ is the value of sag at 100 pounds in the above table. With No. 0 weatherproof wire the sag at 600 pounds is

$$S' = \frac{S \times 100}{T} = \frac{4.86 \times 100}{600} = .81 \text{ feet.}$$

With spans of other lengths the sag or tension will vary in proportion to the square of the length of the assumed span.

That is, $S' = \left(\frac{L'}{100}\right)^2 S$ and $T' = \left(\frac{L'}{100}\right)^2 T$.

With No. 4/0 bare wire for instance the tension with a span of 150 feet at 1 foot sag would be $T' = \left(\frac{L'}{100}\right)^2 T = 1.5 \times 1.5 \times 800 = 1800$ pounds. Or if the tension of the line were 100 lbs. in all the spans, the sag in a 150-foot span of bare No. 4/0 wire would be $S' = \left(\frac{L'}{100}\right)^2 S = 1.5 \times 1.5 \times 8 = 18$ feet.

The foregoing table may be used in the solution of practical problems as follows:

A line of No. 2 weatherproof wire is to be strung on poles with spans of 110, 150 and 200 feet at various points. What

deflection will result if the wire is pulled up to a tension of 300 pounds on all spans?

The sag at 300 pounds on a 100-foot span is

$$S' = \frac{3.18 \times 100}{300} = 1.06 \text{ feet.}$$

On 110-foot spans, $S' = 1.1 \times 1.1 \times 1.06 = 1.28$ feet.

On 150-foot spans, $S' = 1.5 \times 1.5 \times 1.06 = 2.38$ feet.

On 200-foot spans, $S' = 2 \times 2 \times 1.06 = 4.24$ feet.

If 4.24 feet is considered more deflection than is safe on the 200-foot spans, what tension must be used to reduce this to 2.5 feet?

$$T' = 300 \times \frac{4.24}{2.5} = 510 \text{ pounds.}$$

**Expansion and Contraction.** — The changes in the sag of lines due to the expansion and contraction of the wires under varying temperatures are of much importance in the erection of the conductors. Lines erected during the summer months are found drawn very tight during the winter months, while those erected during winter months are apt to be too slack during the summer. Allowance should therefore be made for the temperature at the time the work is done.

The length of the wire in any span may be calculated from the approximate formula

$$W = L + \frac{8\,(S)^2}{3\,L},$$

in which $L$ is the length of span in feet and $S$ is the sag in feet. With a 100-foot span of 1 foot sag

$$W = 100 + \frac{8 \times 1}{3 \times 100} = 100.0266 \text{ feet.}$$

That is, the wire is .0266 foot or .32 inch longer than the span. Likewise, if the length of wire is known, the sag is

$$S = \sqrt{\frac{3\,L\,(W-L)}{8}}.$$

For instance, if a wire should slip on the insulator so as to add .48 inch or .04 foot to the length of wire in the above span, the sag would be increased to

$$S = \sqrt{\frac{3 \times 100}{8}(100.0666 - 100)} = 1.88 \text{ feet, or 19 inches.}$$

The same condition would result if the pole were pulled over so as to shorten the span .48 inch.

The length of wire in a span varies in proportion to the coefficient of expansion and the range of temperature. $W' = W\,(1 + at)$, in which $a$ is the coefficient of expansion, $t$ is the range of temperature in degrees Fahrenheit, and $W$ is the length of wire at the lower temperature. When the length of wire at the higher temperature is known and the contraction is to be computed instead of the expansion, the formula is $W = \frac{W'}{1 + at}$, in which $W'$ is the known length at the higher temperature.

The coefficient of expansion of copper in the form of wire is found to be less than that of copper in other forms. Experiments made by stringing wire between fixed supports and observing deflections at different temperatures indicate that the usual coefficient of expansion, .000095, which applies to copper in other forms, is reduced to about .000040 to .000045 in the case of copper wire. This is borne out by practical experience, as variations of sag are not as great as those determined by calculations based on a coefficient of .000095. For example, with a 100-foot span, strung when the temperature was 10 degrees F., with .75 foot sag, the sag at a temperature of 90 degrees F. would be found as follows:

The length of wire in the 100-foot span at 10 degrees F. is

$$W = 100 + \frac{8 \times .75 \times .75}{3 \times 100} = 100.015 \text{ feet.}$$

At a temperature rise of 80 degrees the length becomes

$$W' = W\,(1 + at) = 100.015\,(1 + .000045 \times 80) = 100.375 \text{ ft.}$$

The increase in length of the wire is therefore .36 foot, or 4.32 inches, and the sag is

$$S = \sqrt{\frac{3 \times 100\,(100.375 - 100)}{8}} = 3.75 \text{ feet.}$$

This condition would be found if all supports were rigid and the conductor inelastic. In practice it is usually the case, however, that the pole supports have a degree of flexibility and resilience which tends to take up part of the slack caused by expansion and to prevent excessive strains being placed on the wire by contraction during cold weather.

It is, however, very apparent from this example that severe strains are likely to result on the longer lines which run some distance without a change of direction, if some allowance is not made for expansion and contraction when the wires are strung.

**Sag at Various Temperatures.** — The following table represents conservative practice in wire stringing at various Fahrenheit temperatures, the deflection being given in inches for convenience.

DEFLECTION IN INCHES.

| Span, ft. | 20° | 30° | 40° | 50° | 60° | 70° | 80° | 90° |
|---|---|---|---|---|---|---|---|---|
| 80 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 90 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 100 | 16 | 17 | 19 | 20 | 21 | 22 | 23 | 24 |
| 110 | 18 | 19 | 20 | 21 | 22 | 24 | 25 | 26 |
| 120 | 18 | 19 | 21 | 23 | 24 | 26 | 27 | 28 |
| 140 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 |
| 160 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 |

These figures are based on the supposition of supports which have some elasticity at the extremes of temperature and with a factor of safety of about 4 at the lower temperatures. This may be lowered somewhat by strains at temperatures lower than o degrees F., but experience has shown that distribution lines erected on the basis of the above table are not subject to excessive breakage during severe cold weather.


Fig. 99. Installation of Small Transformer.

**Clearance from Trees.** — Where primary lines must be carried through trees, care must be taken to provide clearance from limbs as fully as possible. If the necessary permission can be gotten for judicious trimming it should be done. When the trees are very large it is usually preferable to carry the wires through the larger limbs below the main body of leaves. In this case insulators may be attached to

the limbs or an abrasion molding to the wires to prevent wearing of the wire and burning of the limbs. Where trim-

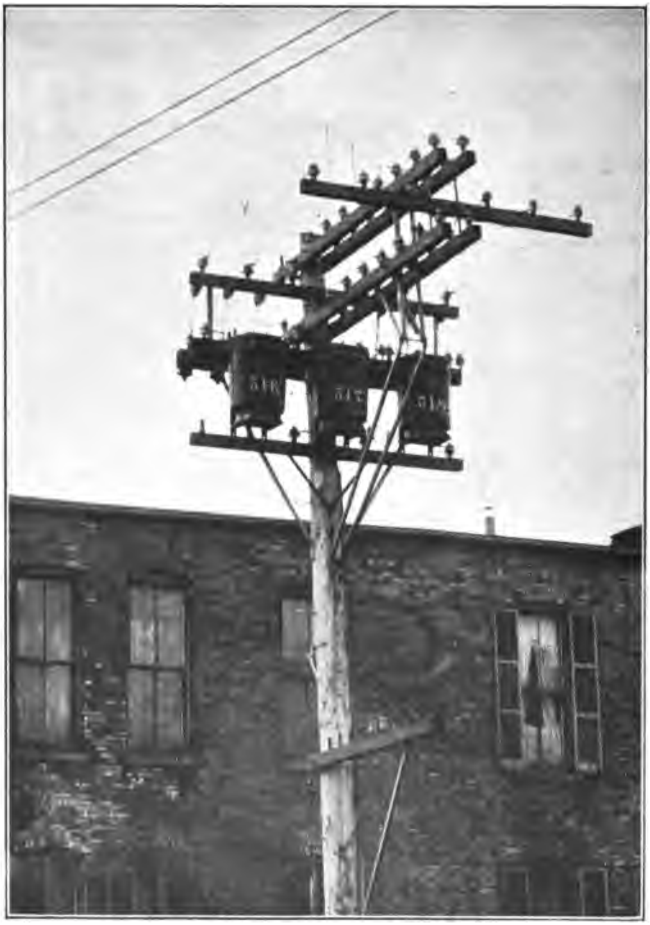


Fig. 100. Transformers with Side-arm Construction.

ming is not permissible to a sufficient extent to be effective, it is desirable to use wire having about $\frac{3}{32}$-inch rubber insulation covered with a layer of tape and two braids.

**Transformer Installation.** — Transformers are commonly supported on cross arms by iron hangers furnished by the

Fig. 101. Large Transformers on Single Pole.

manufacturers. A typical installation of a small unit is shown in Fig. 99. This class of construction is suitable for transformers of capacities up to 20 K.W. With larger units

the cross arms should be double at the top, as they carry most of the weight. One method of making an installation where

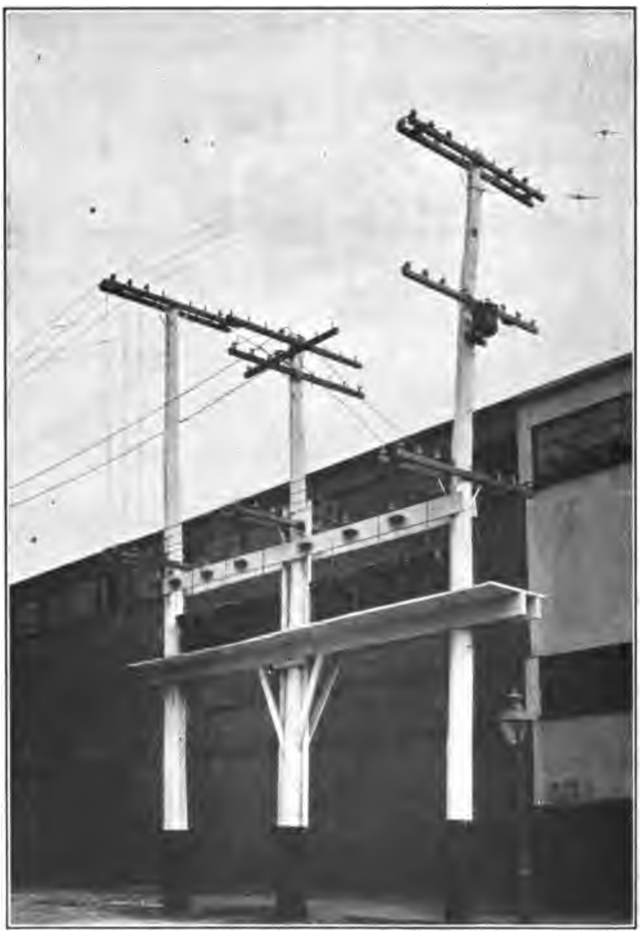


Fig. 102. Installation of Six 50-K.W. Transformers.

side-arm construction is used is shown in Fig. 100. A seven-foot arm brace is used in this case to give room for the larger units.

Where the installation consists of three 15-K.W. transformers or larger, it is advisable to use a larger-sized cross arm than the standard. An arm having a cross section of 4 inches by $5\frac{1}{2}$ inches has been found ample for installations aggregating 90 to 100 K.W., as shown in Fig. 101.

Where very large power is to be served which requires a number of 50-K.W. units which cannot well be put inside the building, they may be safely and conveniently installed on a platform between two or more poles as shown in Fig. 102. The use of units larger than 50 K.W. is usually not convenient, as the weight is difficult to handle and the work of replacement is more expeditious in case of burn-out. The platform in Fig. 102 is supported by timbers 3 inches by 10 inches, bolted to the poles, and the platform is of 2-inch plank. The platform is wide enough to give access on both primary and secondary sides of the units.

**Secondary Grounds.** — To guard against damage to life or property in case a primary wire becomes crossed with a secondary at any point, it is very desirable that the secondary be grounded as securely as possible. This should be done by connecting to water pipes in customers' premises wherever these are accessible to the service entrance. The connection should be made on the line side of the service switch so that it will not be disconnected at any time. Where the ground cannot be reached in the customer's premises, the most practicable method is usually to drive a $\frac{1}{2}$-inch galvanized iron pipe into the ground about eight feet, at the base of a pole near the transformer. If there are more than three spans of secondary main, the grounds should be installed for every 300 feet of secondary line.

On a two-wire 110-volt secondary the ground is connected to one side, while with a three-wire Edison secondary the neutral wire is grounded, making a potential of 110 volts

from either outside wire to ground. On a 220-volt single-phase power secondary the neutral point of the transformer winding should be grounded. With a two-phase four-wire power secondary, the mid point of each transformer winding should be grounded unless the motor windings served are interconnected so as to prevent it. In that event the neutral of one transformer should be grounded. The same procedure should be followed with a three-wire two-phase secondary.

With a star-connected 200-volt or 400-volt three-phase secondary the neutral point of the system should be grounded, giving 115 or 230 volts to ground respectively from each phase wire.

With a delta-connected 220-volt system the ground connection should be made to the mid point of the winding of one transformer. This gives 110 volts to ground from the two-phase wires next to the ground wire and about 200 volts from the other phase to ground. There is some doubt as to the advisability of grounding a secondary when the difference of potential between any wire and ground will be higher than 250 volts, owing to the possibility that shocks from such a system may prove fatal under certain circumstances.

When connection is made to ground through a water pipe the wire should be attached by means of a copper clamp or other connection which may be securely attached to the pipe and wire.

When the connection is made to a pipe at the pole, the ground wire of No. 4 or No. 6 wire is preferably brought down the pole in a half-round wooden molding, to protect the linemen and the public from accidental contact. The ground wire may be soldered to the pipe about a foot above the ground, or may be attached by means of a pipe cap as shown in Fig. 103. This cap may be used to drive the ground pipe and at the same time produce a driven contact between wire and pipe. The pipe is usually driven down near to the

ground line with this cap in order to minimize the amount of exposed surface.

In rocky country it is sometimes necessary to run a ground wire throughout the denser parts of the system and connect it at one point to a well-made ground. This is, of course, an expensive method and is not used except as a last resort.

Fig. 103. Ground Wire Connector.

**Service Connections.** — Service drops should be tapped near the secondary line insulators and may be supported by them when they can be carried at such an angle from the pole that they will clear properly. Where they leave the pole at approximately right angles they may be supported from iron brackets or from insulators on a buck arm provided for the purpose. If there are several services taken from the same pole the use of a buck arm is the best method, as services can be taken to both sides of the thoroughfare in any desired number from one buck arm.

Where separate power and light services are maintained, the use of a six-pin buck arm provides facilities for both classes of service. The attachment of service wires to buildings is one of the most troublesome details of distribution work, owing to the varying character of buildings, lengths of drops and angle of approach. With frame buildings wooden brackets

and spikes are used to some extent for wires up to No. 2 and spans up to 60 or 75 feet. With brick or stone buildings, however, this construction is not reliable. Where three-wire service is required, the necessity of drilling bolt holes for each wire and the necessity for reliable construction have led to the development of various forms of iron brackets which are supported by expansion bolts when attached to brick or stone buildings.

In making a loop on series arc circuits an iron fixture having two pins and so arranged that it can be put in place of a line pin and known as a break arm, is used.

Arc lamps for street lighting are supported by a crane from a pole or from a cable strung between two poles and equipped with a pulley by which the lamp can be lowered for trimming purposes. The latter method is usually the less expensive and is used except where the installation of two poles is not practicable or is considered unsightly. In some of the larger cities it is usual to mount lamps on a short bracket without provision for lowering the lamp. In this case the pole is stepped so that the trimmer climbs the pole to trim the lamp.

**Arrangement of Wires.** — The position of wires on the cross arms should be assigned according to a systematic plan. Circuits should be kept on the same side of the pole and on the same pins throughout their course, to facilitate location of trouble and to eliminate the possibility of accidents to workmen or property due to misunderstandings. In general, through lines and the highest voltages should be carried on the upper arms. Distributing mains and arc circuits supplying lamps in the vicinity should be carried near the bottom of the line. Secondaries should be carried on the lowest arm to facilitate service work.

The lowest voltages should be carried on the pole pins.

Where side arms are used the primary wires should be carried at the outer end of the arm. The wires of a given circuit should be carried on adjacent pins and the neutral of low-tension or secondary wires should be carried in the middle. On four-wire three-phase lines the neutral should be carried at one side of the phase wires and, except on side arms, on one of the pole pins. With side arms it should be carried on the side of the circuit nearest the pole. In carrying connections across the pole transformers or services, one side of the pole should be left free for climbing.

**Joint Occupancy.**—Where poles are occupied jointly by electric light and telephone or telegraph companies, the lighting wires should always occupy the upper part of the pole, as the signaling wires are more likely to break than the lighting lines.

A clearance of about 5 feet should be maintained between the lower lighting wires and the upper signaling wires. This may be reduced to $3\frac{1}{2}$ feet between the bottom of a transformer and the upper signaling wires. These clearances are necessary for the safety of linemen who may be working on either set of wires.

The use of a joint line of poles is preferable to separate lines on thoroughfares where there are many service drops. With lines on opposite sides of the street, the service drops of the lighting company must pass under or through the lines of the signaling company on the other side and vice versa. This introduces many dangerous situations which are eliminated when all drops are taken from one set of poles.

It is usually very undesirable to erect a separate line on the same side of the street with an existing line.

With alley lines the use of joint poles is the safest method unless the lighting line is carried high enough to permit all service wires to be carried above the signaling line. This involves extra expense and is objectionable on that account.

# CHAPTER X.

## UNDERGROUND CONSTRUCTION.

THE use of underground construction has been general in the larger cities from the beginning of the electric lighting industry. Considerations of appearance and space prevented the use of overhead lines in the congested parts of the large cities where the early market for electricity was found. The greater first cost was found to have been well justified in the increased security to the service of important consumers to whom an interruption meant financial loss. The development of many of the large city systems proceeded at such a rate that in any event overhead construction would have become physically impracticable within a few years on account of the number and size of the feeders which were required to supply the network.

**Edison Tube System.** — The underground system devised by Edison was the earliest one to be commercially adopted, and much of this class of equipment is still in service, though other methods are now preferred. The Edison system remained standard for low-tension distribution for about fifteen years and was in many ways an admirable plan of low-tension distribution. It consisted of 20-foot lengths of iron pipe inside of which there were copper rods embedded in a bituminous compound designed to exclude moisture and to insulate the opposite polarities from each other and the pipe. The rods were wound with a wrapping of jute, to prevent their sagging together, and were further held rigidly apart by separators at the ends. These 20-foot lengths were made in

various sizes of conductor from No. 1 up to 500,000 c.m. for mains and up to 1,000,000 c.m. for feeders.

The Edison Company adopted what became known as the Edison wire gauge for their product. This gauge specified the number of thousands of circular mils in the conductor. The pipe with its conductor was called a tube, and a tube having conductors of 250,000 c.m. was called a 250 tube, or a tube with No. 1 B. & S. conductor was called an 81 tube.

Fig. 104. Edison Tube Junction Box.

Such a gauge became necessary because most of the sizes of tubes were larger than the largest size of any existing standard wire gauge.

Sections of tube which were designed for use as distributing mains were made with three conductors of the same size, while those designed for feeders were often made with one conductor about half the area of the others. This small conductor was used as the neutral, as the load on the feeder was nearly balanced and little capacity was required in the neutral.

Feeder tubes were also provided with three small wires which served as pressure wires to indicate the feeder end pressure at the station or substation.

The sections of tube were laid in the ground without other protection than would be given water or gas pipes. The copper rods were joined by means of soldered lugs with a stranded flexible connector. These connections were enclosed in cast-iron couplings, which were filled with hot compound after being bolted in place on the tubes. At intersections the tubes were interconnected through junction boxes, which carried the necessary fuse clips and nuts by which a main was automatically disconnected in case of breakdown, or could be opened by repair men for testing purposes. These boxes were made so that 4, 6, 8 or 10 tubes could be brought together in one box, as was necessary at the intersection of two streets where a feeder was tied in, and where there were lines going each way on both sides of the street.

Lines were carried along each side of the street near the curb in order to facilitate the introduction of services into consumers' premises. A single line was run where the consumers were scattered and where the alleys were used. Service connections were made by a T connection applied at any joint in the line. The service tube was carried through the building wall into the sidewalk area or into the basement of the building. Where the buildings were not built out to the property line, the service was extended underground across the consumers' premises or brought up on a pole at the lot line and carried thence overhead to the building. The expense of the line across the private property was usually borne by the consumer, and the decision as to the method of installation commonly rested with him in such cases.

The Edison tube system was the standard method of distributing low-tension current underground until about the

year 1897, when cables drawn into ducts began to be employed for the heavy feeders. This change was made on account of

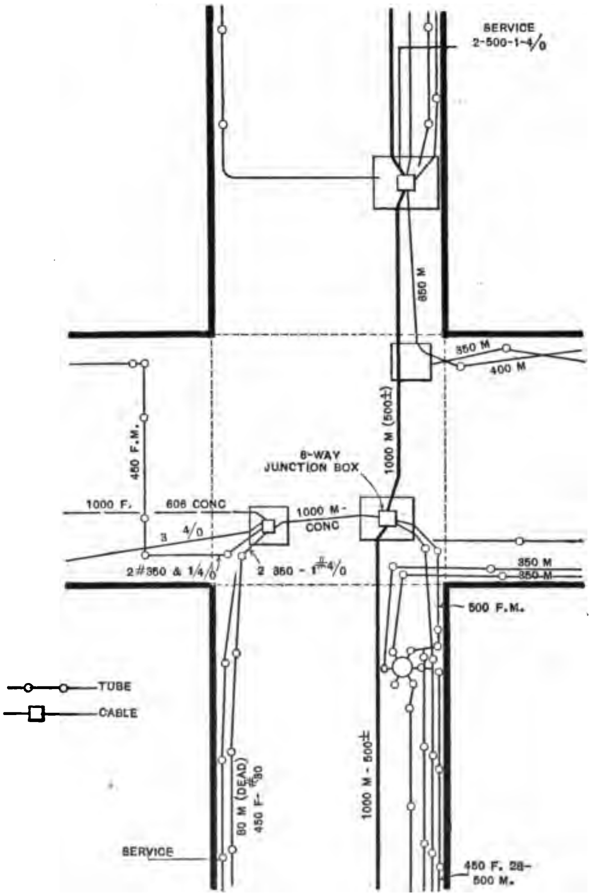



Fig. 105. Edison Tube and Cable System.

the inability of the tube feeders to carry overloads without melting the compound in the joints and causing burn-outs. With cable it was found that the copper could be run with

heavier loads, and therefore more economically from an investment standpoint.

The necessity of opening street pavements in each case where repairs were made involved considerable expense, as several openings were usually made before the trouble could be definitely located.

The feeder system and the heavier distributing mains were therefore gradually worked over to a cable system as rapidly as reënforcement was needed from year to year. The systems as they exist, therefore, embody a combination of cable and tube work such as is shown in Fig. 105, which illustrates the feeders and mains at an important street intersection in Chicago. The tube system is not being generally extended at the present time, but on side streets where no through lines are required and the load is not heavy, the simplicity of the tube system is retained by laying a single 3-inch iron or bituminized fiber duct into which lead-covered cables are drawn.

Service connections are made in a manner similar to the tube services, the joints being enclosed in a T coupling box of iron. The cost of such construction is about the same as that of Edison tube work, and it is therefore supplanting Edison tube work in cases where such construction is desirable.

**Early Conduit Systems.** — The early alternating and series arc systems which were installed in situations requiring underground constructions were unable to use a system similar to the Edison tubes because of the higher voltages employed. They were therefore compelled to seek other means of installing their conductors. A variety of materials was tried, but the method was that of a draw-in conduit system with manholes for handling the cables in nearly every case. One of the earliest was the Dorset system, which consisted of sections

of multiple duct made up of an asphaltic concrete joined together by pouring hot compound around the joints. These joints failed to remain in alignment and the asphalt ducts became distorted, so that the work of installing cable became difficult if not impossible.

Creosoted wooden pump log was tried because of its ease of jointing and low cost. It was very satisfactory for some classes of work, but was too short-lived for important lines, and took fire too easily in case of failure of cable, the creosote with which it was impregnated being inflammable.

Paper tubes impregnated with bituminous compound were tried in some cases. These were laid in asphalt and the conductors were drawn in without insulation. It was expected that the insulating qualities of the paper tubes would be sufficient to be practical. The presence of moisture, however, could not be wholly prevented and the tubes therefore absorbed water at the manholes and this caused the conductors to become short-circuited and burn out. It was practically impossible to make repairs, and the system failed.

In another plan the bare conductors were drawn through 1-inch holes in a wooden tube which was surrounded by an iron pipe and immersed in oil. The manholes were also kept partly filled with oil to cover the ducts, but as moisture could not be excluded and the difficulty of adding to or repairing high-tension conductors was great, this system failed.

Other systems were developed in which the ducts were intended to provide insulation for the conductors, but experience proved that it was not at all practical to maintain such a system, and all such attempts were abandoned.

The efforts of engineers were then directed to systems in which the construction was more nearly fireproof, of greater durability, and yet economical to construct and maintain.

This naturally led to the development of methods in which the insulation was applied to the conductor and the conduit

was of some fireproof material which would be durable underground.

Among the earlier forms of duct of this sort was one which consisted of sheet-iron tubes lined with cement. It was made in 4-foot lengths, with ferrules at the ends to preserve the alignment, and when properly laid obviated many of the difficulties experienced with the earlier forms of duct. A considerable amount of it was installed in some of the larger cities. Where it has been subjected to cable burn-outs with large power behind, it has been found, however, that the cement does not hold up under the heat of an arc, and that the metal sheathing is apt to assist in the spread of the short circuit. The use of this form of conduit has, therefore, not been continued in recent years.

As an improvement over this type a conduit made entirely of concrete and known as stone pipe was developed. This is made in 4-foot lengths and jointed with metal ferrules to preserve the alignment, single duct only being used. The conduit line was laid in concrete, making a solid and durable duct system. The cost is about the same as that of other forms of construction, but the concrete pipe in 4-foot lengths is fragile so that the breakage is greater than in the other forms of duct. The pipe does not acquire its full strength and hardness until it has been seasoned 30 to 60 days after being molded, and this necessitates storage facilities. Various forms of fiber conduit have been used also to a limited extent. These are laid with concrete around and between them so that as the fiber may disintegrate in after years there will remain a concrete duct system. These systems are not yet of sufficiently long standing to permit definite conclusions to be drawn.

While these various forms of duct were being tried out, other engineers were introducing ducts of terra cotta and clay tile. These materials being fireproof and of indefinitely long

life, it only remained to work out the best form of duct and the most durable way of laying it. Multiple and single duct was tried, and the alignment and security from outside interference were gotten by protecting the ducts by concrete or creosoted plank. The supply of clay is abundant and the expense therefore somewhat less than with other ducts. This class of construction is now therefore the most generally used in distribution work where a draw-in system is employed.

**Design of a Conduit Line.** — In the design of a draw-in duct system, the number of ducts, the size of manholes and their location are the most important considerations.

The *number of ducts* must be fixed by the particular requirements of the route to be followed. There must be sufficient to care for the local distribution, for distributing feeders, for transmission lines and for possible future requirements. The distributing mains for a low-tension system usually fill one duct, but with alternating mains and underground secondaries two ducts must be reserved in many parts of the system. The feeder and transmission line requirements are fixed by the proximity to stations. The reservation of duct space for future requirements is very important if the system is a growing one, as the expense of adding a few ducts at a later date is much larger than if they are laid when the trench is open. It is therefore desirable to lay sufficient reserve ducts in advance to care for probable requirements for at least five years ahead. It is not advisable to lay less than four ducts in a line except on side streets where there is no probability that the line will ever become part of a through line. In such cases two duct lines are installed where a single pipe with a low-tension main will not meet the requirements.

The maximum number of ducts which it is advisable to put into a line is governed somewhat by the local conditions but chiefly by considerations of safety to the cable equipment.

The space available on walls of manholes for training cables is limited, and if more than 20 or 25 ducts full of cable are carried through a manhole a large part of the load of the system is endangered by a failure on any one of the cables. The security of the service as a whole is much improved by having conduit lines subdivided sufficiently to prevent a complete interruption of service in case of a serious manhole burn-out or an accident to the conduit system. Where conditions are such that a very large line must be used, a measure of protection may be had by separating one-half of the duct line from the other by a 6-inch concrete barrier and building double manholes for the two sides of the line with an 8-inch brick partition through the middle of them. A line having more than four ducts in each layer is to be avoided where possible on account of the difficulty of properly training the cables. The arrangement of ducts shown in Fig. 106 is a desirable one where more than 16 ducts are laid in a line.

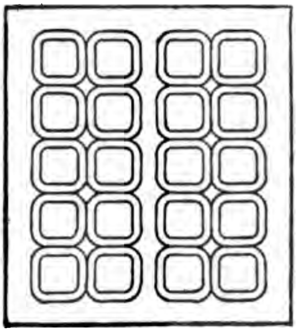


Fig. 106. Divided Arrangement of Ducts.

**Location of Manholes.** — The use of a draw-in system involves the construction of vaults called manholes at all points where the cables must be jointed or where lines change direction.

Where long runs occur without intersecting other lines, manholes must be provided with sufficient frequency to permit the drawing in of cable without overstraining the cable insulation. This usually requires that they be not over 500 feet apart, and with large cables which nearly fill the duct 400 feet is a safer limit.

The location of manholes on a length of line which is not

intersected by other duct lines at each block should be made as far as possible with a view to their being used as intersection points later. That is, they should be located so that any conduit line built on an intersecting street later may be connected with existing manholes. It is impossible to predict with certainty which side of an intersecting street will be used, but the location of manholes at street and alley intersections will minimize the necessity for duplication. Where distribution by overhead lines in alleys with underground lines on the street is used, manholes should be put opposite alley intersections where it is necessary to locate them between streets. It is also advisable in such distribution to locate manholes opposite alley intersections where lines are likely to be connected from the duct system to the pole system.

The number of manholes required in blocks where numerous underground service connections are required is dependent somewhat upon local conditions, but must usually be sufficient to enable lateral pipes to be brought in to sub-sidewalk areas or basements at intervals of 25 to 100 feet. In the denser portions of the system this results in the location of small manholes at intervals of 75 to 125 feet, while in other parts they may be 150 to 200 feet or more apart. In distribution by means of underground transformers and a secondary network where the load is dense, it is usually necessary to build extra large manholes for the transformers in order to get sufficient room and proper ventilation.

**Design of Manholes.** — The size and shape of manholes are varied to suit the requirements in different situations. Manholes located in a straightaway line should be so designed that the cables may be trained around the sides with a minimum of waste cable and yet with sufficient space to enable a jointer to work efficiently. Such a manhole is illustrated in Fig. 107. The oval shape permits of easy training of cable,

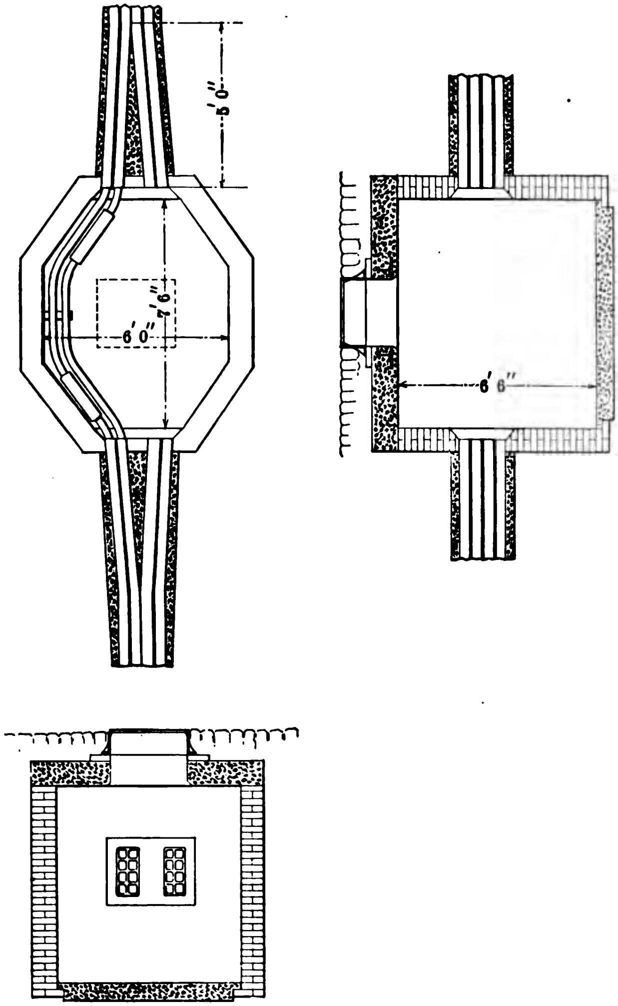



Fig. 107. Manhole for Through Lines.

and the width of four feet is ample to allow the jointer room to work with any number of ducts up to nine. Where the line turns a corner or intersects another duct line, a design must be used which gives room for cables going both ways and which will afford room for work as well. At such points a square design is preferable, as shown in Fig. 108. The smallest size ordinarily used for such points is five feet square. Where many cables are involved or where room is required for low-tension junction boxes or transformers, dimensions of 8 feet by 8 feet or larger are often necessary. Where it is likely that many splices will be made or other work of construction or maintenance done frequently, it will be found to be most economical in the long run to provide manholes of ample size for convenient working space. The money saved by reducing the dimensions of a manhole one foot may be spent several times over in extra cost of work done on cables in the manhole in later years.

In a growing system it is a matter of judgment as to what the requirements in the way of space are likely to be. The space required for cables is fixed by the number of ducts coming into the manhole, and this must be sufficient to allow of training these cables safely and with a reasonable degree of accessibility for repairs or changes. The probable installation of junction boxes or transformers must be taken into account also. In practice it is usual to provide manholes 5 feet by 5 feet at junctions where there are eight ducts, that is, where two 4-duct lines cross, 6 feet by 6 feet where there are 12 to 18 ducts, 7 feet by 7 feet where there are 20 or more, and larger as the needs of the case may require.

The size and shape of manholes in congested districts are often governed by local obstructions such as gas or water mains and services or the conduit lines of other public service companies. Manholes must frequently be built so as to in-

clude a gas or water main, and the size must be increased to get the necessary space.

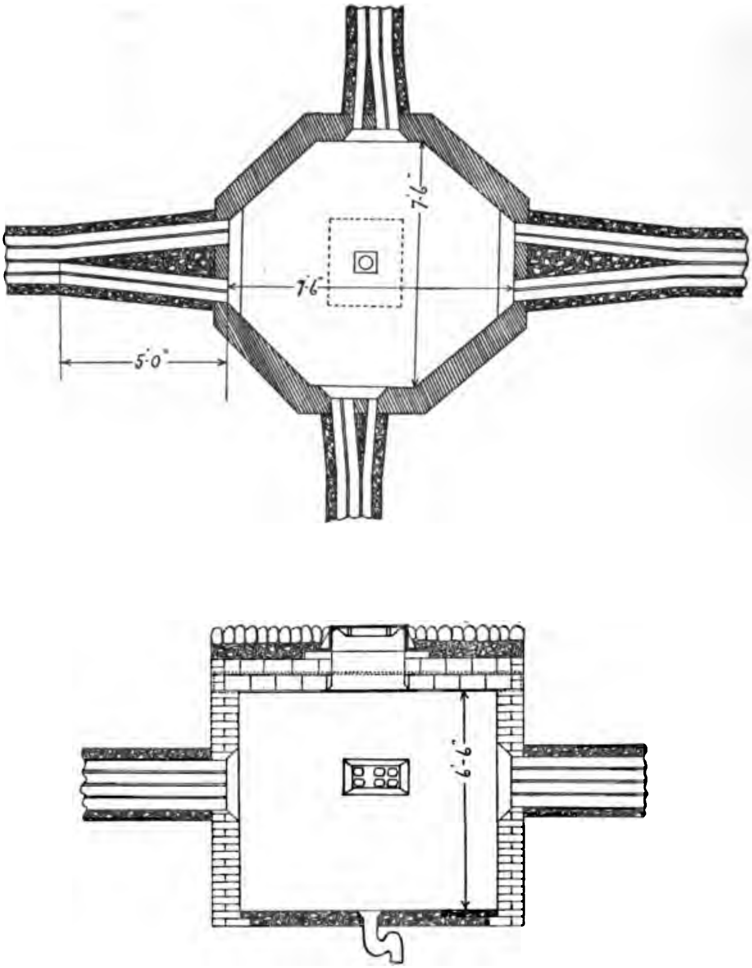



Fig. 108. Manhole for Intersections.

The depth of manholes must be sufficient to give head room and yet should preferably not be so great as to carry the floor of the manhole below the sewer level. Small distribu-

tion manholes which are used only for service connections may be more shallow than larger holes where work is done frequently. Service manholes may be 5 feet inside, while junction manholes should be 6 or 7 feet from roof to floor. In some cases a shallow form of manhole known as a handhole is used for distribution laterals. These are made about 3 by 4 and 3 to 4 feet deep. They are placed above the conduit line, so that only the top row of ducts enters the handhole. The distributing mains are thus accessible for service taps, and the through lines in the lower ducts are not in the way. Service laterals are usually laid just under the paving, so that they enter the handhole at a convenient level. Handholes should have covers large enough to afford access to the distributing main.

**Service Connections.** — The arrangement of service laterals or subsidiary connections from the main duct line to consumers' premises is a matter of much importance, as it forms a large part of the underground investment in congested districts. Local conditions often fix the character of the design, so that no universal method can be laid down as better than all others. In some cities a separate service lateral is not required for each building into which service is to be introduced and the laterals may be placed at intervals of 75 to 100 feet or more, the intermediate buildings being connected by means of interior wiring through sub-sidewalk areas or building basements. This method is much less expensive than that required in cities where each building must have its own service connection, as it requires fewer distributing handholes or manholes and a much less mileage of lateral pipe and service cable.

Where service laterals can be spaced 100 feet or more apart a single duct line is sufficient to care for the service on both sides of the street. Lateral connections are run to

each curb or building line from the service manholes. With a street more than 100 feet wide, it may be more convenient

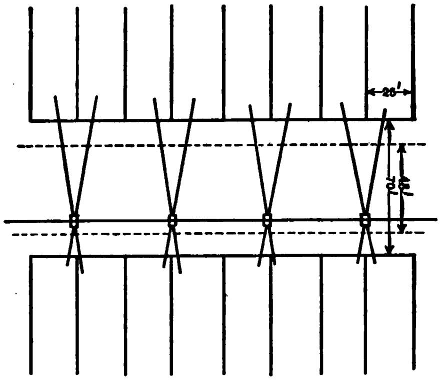



Fig. 109. Service Handholes and Laterals.

to use two duct lines to save the long laterals. In very congested districts it is advisable in this class of construction to put in double laterals each way to facilitate repairs or changes in the cable work or to give emergency service to important consumers.

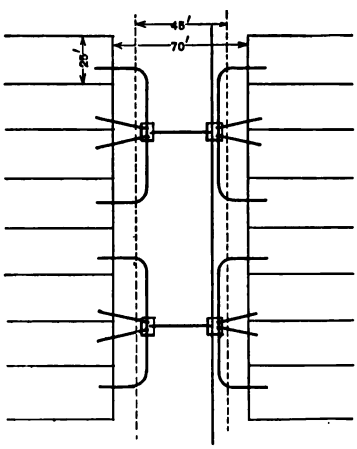



Fig. 110. Double Handholes for Service Connections.

Where separate service is required for each building, this plan may result in the installation of manholes or handholes at intervals of 50 feet as in Fig. 109, where buildings are on 25-foot lots and service is required in nearly every building. In such cases it is less expensive in the long run to establish service handholes at intervals of about 100 feet on each side of the street. The arrangement

shown in Fig. 110 is the result worked out in a street 70 feet wide, with 40 feet between curb lines. This arrangement requires less lateral cable and pipe and is the most feasible arrangement in streets where there are car tracks under which laterals must be carried. The advantage of the construction shown in Fig. 110 increases with the width of the street. It is also an advantageous plan where there is a parkway in which the laterals can be laid, no paving being disturbed except at the street intersections.

**Location of Duct Lines.** — In the location of a duct line the presence of other piping systems, duct systems, sewer manholes and the like must be taken into account. It is desirable to select the side of the street which is least obstructed by such obstacles. The municipal records should be consulted to get the location of the piping and sewer systems, if such records are kept in available and accurate form. Other duct systems are readily located by the manhole covers which appear on the surface. In crowded streets and where records are not available, time is sometimes saved by excavating a test trench across the street at several points for the purpose of locating the piping and other systems which cannot be identified from the surface.

**Specification for Tile Duct.** — Tile duct is made of clay which is worked up in a pug mill to the proper consistency, passed through a press from which it emerges in the desired shape, carefully dried and burned in a kiln until it is thoroughly vitrified. It is then given a salt glaze and allowed to cool slowly.

The quality of the duct is affected by many of the processes very materially and it is therefore important that it be purchased under careful specifications. Some of the more important points follow:

The clay should be of such composition that it will be free from gravel and will work up into a solid homogeneous mass. 60 per cent fire clay and 34 per cent shale make a very desirable combination.

The duct when molded and dried should be burned through but not scorched or fused. The glaze should thoroughly cover the inside of the ducts so that they will present a smooth surface to the cable.

Single duct should not have a bend of over $\frac{1}{8}$ inch from a straight line and multiple duct should not have a more than $\frac{3}{16}$ inch bend. Twisted or distorted pieces should be rejected, as they cannot be lined up and may interfere with rodding the duct.

No duct having salt blisters or drips which project more than $\frac{1}{8}$ inch inside or $\frac{1}{4}$ inch outside should be used.

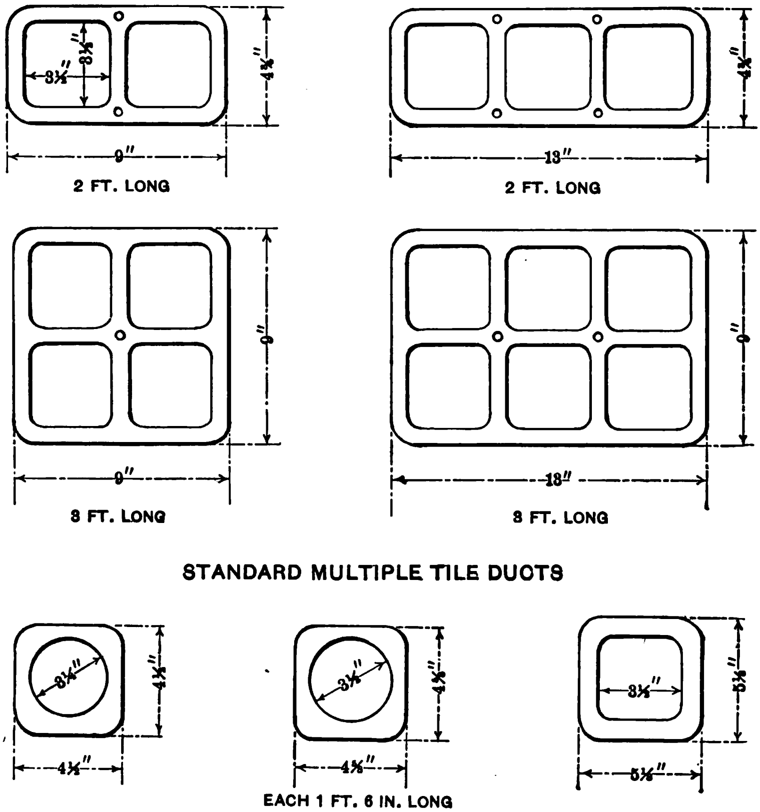
Air- or fire-checked pieces should not be accepted.

The test for straightness should be made by passing through the duct a mandrel of the length of the piece and $\frac{1}{8}$ inch smaller than the inside of the duct. If the mandrel will not pass, the duct is too crooked to be safely installed.

If the tile is properly vitrified it will give a clear ringing sound when struck with a piece of tool steel $\frac{1}{2}$ inch by $\frac{3}{4}$ inch. If not, it gives a dead sound which indicates softness and porosity, which will result in too high a rate of breakage in handling if accepted.

**Forms of Duct.** — Tile conduit is made in single- or multiple-duct pieces. Single-duct pieces are usually about 18 inches in length, while multiple duct may be made 36 inches long. The greater length is desirable in reducing the labor of laying, but is not practicable in single duct on account of breakage. The dimensions of ducts in general use are shown in Fig. 111. The duct having a square hole is preferable, as cable may be pulled into it more easily. Multiple duct is

somewhat cheaper than an equal number of single ducts, as it requires less labor to lay it. In a large system, with the danger of injury when an arc is maintained in the duct, it is




STANDARD SINGLE TILE DUCTS

Fig. 111. Forms of Tile Duct

usually considered preferable to use single duct to secure the advantage of having two thicknesses of tile between adjacent ducts. This protects the cables in adjacent ducts from injury in case of burn-outs. The single duct also has the further

advantage that the joints may be staggered, thus making it much more difficult for the heat of the arc to pass to the adjoining ducts.

**Installation of Conduit Lines.** — In laying a line of ducts the grades must be carefully established so that the duct line will tend to drain toward the manholes. If pockets are formed, the standing water is likely to freeze in winter weather and injure the insulation of the cables and break the tile.

It is especially important that manholes where work must be done frequently or where transformers or junction boxes are installed be connected through a tap to the sewer. The accumulation of water in such a manhole may start trouble or may seriously delay repair work which is urgent.

The conduit line must be protected, when laid in public thoroughfares, from future excavators. It should also be made secure against the possibility of getting out of alignment and thus injuring the cable or making it impossible to pull cable in or out. In view of these considerations it is usual to surround important lines with concrete on all sides to a thickness of three inches. This makes an envelope thick enough to support short sections around which excavations may be made later and also protects the tile from the laborer's pick. In some cases it is considered advisable to lay 2-inch plank on the top of the conduit as a warning to those digging. The concrete when set acts as a watershed to a large extent and minimizes the entrance of leaking gas into the conduit system.

The construction of manholes is dependent largely upon the particular use to which they are to be put and must often be modified to suit conditions which vary widely. The walls of manholes are made of brick or concrete.

Where excavations can be made without interference with other piping or duct systems, manholes may be economically

constructed of concrete according to a standard design for which forms may be used. When any obstruction is encountered the form is not practical and walls must be built up of brick. In most cases the floor may be made of concrete without difficulty, as no forms are needed.

The brick should be of the quality known as sewer brick and should be laid up with a good cement mortar, an 8-inch wall being ample for the requirements in most cases. The roof must have sufficient strength to support the heaviest street traffic, and its design therefore varies with the size and shape of the manhole. In general the necessary strength is secured by the use of steel beams as a framework. Worn rails are sometimes a cheap form in which to purchase steel for such purposes. The framework is filled in with brick, concrete or terra cotta building arches. Manhole covers and frames are made of cast iron of rugged design, the top surface of the cover being a broken one to prevent accidents to teams or pedestrians. In heavy lines it is found very desirable to provide openings in the covers for purposes of ventilation. The amount of heat liberated in a heavy line of low-tension cables is very appreciable, and ventilation must be provided to keep the temperature as low as possible. The ventilated manhole is also much less likely to accumulate gas in sufficient quantity to cause an explosion or to interfere with work. Serious explosions have occurred in manholes which were not ventilated.

**Cost of Conduit Construction.** — The cost of underground work has been discussed by several writers, notably W. P. Hancock, who presented a paper which appears in the 1904 Proceedings of the National Electric Light Association, and Louis A. Ferguson, whose paper was read before the International Electrical Congress at St. Louis in 1904 and appears in the proceedings of that body.

The figures given by Mr. Hancock represent experience in the city of Boston primarily, while those of Mr. Ferguson were taken from work done in the city of Chicago.

The figures agree quite closely in the final results as to total cost, though arrived at differently, and they may therefore be taken as applicable to those portions of any city where a high grade of construction is justified. Less expensive work can be and is sometimes done in the outlying portions of a city, by omitting parts or all of the concrete and depending upon plank for protection. The use of such construction must be a matter of judgment, the local conditions and importance of the service being the governing considerations.

The figures in Table IV are those of Hancock, showing the cost of conduit without manholes for a 15-duct line laid up with single tile. Table V shows the elements of cost for a 5 by 5 by 7 feet deep manhole according to Hancock. The walls are of brick and the floor and roof of concrete. Table VI shows the cost of duct lines of various sizes laid up from single tile without manholes, as given by Ferguson.

The costs of repaving are approximately as follows: Cedar block 60 cents, macadam 50 cents, granite blocks $1.00, asphalt $3.25 per square yard. These costs are higher if it is necessary to open up paving within the period in which the contractor's reserve is still effective, as the opening can be made only with his permission and subject to the terms dictated by him for repaving.

Table VII gives the cost of the more common sizes of manholes, as reported by Ferguson. These figures include sewer connections, concrete roof and floor, with brick walls, but not repaving. The dimensions are given with depth from floor to roof inside the manhole as the last figure in each case.

TABLE IV. — COST OF 15-DUCT LINE.

| | PER DUCT FOOT. | |
|---|---|---|
| Lumber at $15 per M | $.0105 | |
| Concrete at $4.85 per yd | .0231 | |
| Mortar at $3.98 per yd | .0026 | |
| Tile at $.05 per ft | .0502 | |
| Total material | | $.0864 |
| Excavation and filling at 15 cts. per hour | .0266 | |
| Placing lumber at 20 cts. per hour | .0004 | |
| Placing concrete at 15 cts. per hour | .0029 | |
| Placing mortar at 25 cts. per hour | .0016 | |
| Laying tile at 50 cts. per hour | .0040 | |
| Hauling away dirt at 50 cts. per hour | .0047 | |
| Total labor | | .0402 |
| Inspection, 50 cts. per hour | | .0033 |
| Engineering expenses | | .0214 |
| Incidentals, 5 per cent | | .0116 |
| Per duct ft | | $.1629 |

TABLE V. — COST OF 5×5×7 MANHOLE.

| | | |
|---|---|---|
| 23.7 cu. ft. concrete at $.202 | $4.78 | |
| 2500 bricks at $9.00 | 22.50 | |
| 1013 lbs. railroad iron at $.0125 | 12.67 | |
| Manhole frame, 962 lbs. at $.015 | 14.43 | |
| 1⅛ yds. mortar at $3.98 | 4.47 | |
| Sewer trap | 5.65 | |
| 30 feet sewer pipe at $.30 | 9.00 | |
| Total | | $73.50 |
| Excavation and filling 785 yds. at $.0278 | $21.82 | |
| Repaving at $1.44 per sq. yd | 11.95 | |
| Removing dirt | 4.30 | |
| Laying brick | 7.00 | |
| Total labor | | 49.07 |
| Grand total | | $122.57 |

TABLE VI. — APPROXIMATE COST OF SINGLE-DUCT CONDUIT (IN CENTS) PER DUCT FOOT.

| No. of ducts. | Cost of repaving per square yard. | | | | | | |
|---|---|---|---|---|---|---|---|
| | | $0.50 | $1.00 | $1.50 | $2.00 | $3.00 | $3.50 |
| 2 | 24 | 29 | 34 | 38 | 43 | 52 | 56 |
| 4 | 22 | 25 | 27 | 30 | 33 | 38 | 41 |
| 6 | 20 | 22 | 24 | 26 | 28 | 32 | 34 |
| 9 | 19 | 21 | 22 | 24 | 25 | 28 | 30 |
| 12 | 19 | 20 | 21 | 23 | 24 | 26 | 28 |
| 16 | 18 | 19 | 20 | 21 | 22 | 24 | 25 |
| 20 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 17 | 18 | 18 | 19 | 20 | 21 | 22 |
| 30 | 16 | 17 | 17 | 18 | 19 | 20 | 21 |
| 40 | 16 | 17 | 17 | 18 | 18 | 19 | 20 |
| 50 | 16 | 16 | 17 | 17 | 18 | 19 | 19 |

The number of duct feet and manholes of each size having been laid out on a plan, the cost of the conduit line may be estimated from these tables with fair accuracy, the kind of paving and other local conditions being known.

For instance, with a macadam-paved street, what will be the cost of a 4-duct line 1000 feet long with two 5 feet by 5 feet by 6 feet and two 3 feet by 3 feet by 4 feet manholes? From Table VI the cost of a 4-duct line with paving at 50 cents is .25 per duct foot. There being 4000 duct feet the conduit proper will cost $1000. From Table VII the cost of the two 5 feet by 5 feet by 6 feet manholes will be $123.23 each, or $246.46, while the two 3 feet by 3 feet by 4 feet manholes will cost $46.50 each, or $93. The 5 feet by 5 feet by 6 feet manholes require 10.67 square yards of repaving each, or 21.34 yards, and the two small manholes require 8 yards. The cost of repaving 29.34 square yards at 50 cents will therefore be $14.67. The entire cost of the work will therefore be

| | |
|---|---|
| Conduit | $1000.00 |
| 2 large manholes | 246.48 |
| 2 small manholes | 93.00 |
| Repaving | 14.67 |
| Total | $1354.15 |

TABLE VII. — COST OF MANHOLES, EXCLUSIVE OF COST OF REPAVEMENT.

| Material. | 3'×3'×4' | | 4'×5'×5' | | 5'×5'×6' | | 6'×6'×6' | | 7'×7'×6' | | 8'×8'×6'[1] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quan. | Amt. | Quan. | Amt. | Quan. | Amt. | Quan. | Amt. | Quan. | Amt. | Quan. | Amt. |
| Excavation and removal of dirt at 87½ cts. per cu. yd.... | 3.70 | $3.24 | 7.77 | $6.80 | 16.30 | $14.26 | 19.00 | $16.63 | 24.00 | $21.00 | 29.63 | $25.93 |
| Brickwork — sides at $9.50 per cu. yd................ | 1.67 | 15.86 | 2.92 | 27.74 | 4.17 | 39.62 | 4.50 | 42.75 | 5.17 | 49.12 | 5.83 | 55.39 |
| Concrete — bottom at $7 per cu. yd.................. | ...... | ...... | .37 | 2.49 | .56 | 3.92 | .67 | 4.69 | .91 | 6.37 | 1.18 | 8.26 |
| Concrete — top at $8 per cu. yd.................. | .56 | 7.00 | .96 | 7.68 | 1.35 | 10.80 | 1.55 | 12.40 | 2.01 | 16.08 | 2.50 | 20.00 |
| Iron in roof at 3 cts. per pound | 105 lb. | 3.15 | 129 lb. | 3.87 | 153 lb. | 4.59 | 178 lb. | 5.34 | 215 lb. | 6.45 | 227 lb. | 6.81 |
| Sewer connection and permit at $25 each.............. | ...... | ...... | 1 | 25.00 | 1 | 25.00 | 1 | 25.00 | 1 | 25.00 | 1 | 25.00 |
| Trap and backwater valve at $6.50 each.............. | ...... | ...... | 1 | 6.50 | 1 | 6.50 | 1 | 6.50 | 1 | 6.50 | 1 | 6.50 |
| Sewer grates at 30 cts. each.. | ...... | ...... | ...... | .30 | ...... | .30 | ...... | .30 | ...... | .30 | ...... | .30 |
| Frame and cover at $15 each . | 1 | 15.00 | 1 | 15.00 | 1 | 15.00 | 1 | 15.00 | 1 | 15.00 | 1 | 15.00 |
| Supervision and incidentals... | ...... | 2.25 | ...... | 2.25 | ...... | 2.25 | ...... | 3.25 | ...... | 3.25 | ...... | 3.25 |
| Totals................ | | $46.50 | | $97.63 | | $123.24 | | $132.06 | | $149.07 | | $166.44 |
| Sq. yds. repaving required.... | 4.00 | | 8.89 | | 10.67 | | 12.00 | | 13.89 | | 16.00 | |

[1] Last dimension is depth. Depth of manhole given in the clear inside dimension

The total cost including manholes and repaving is therefore equivalent to 33 cents per duct foot. If the paving had been asphalt at $3.25 per yard the conduit proper would have cost 40 cents per duct foot, or $1600, and the manhole repaving would have been $95.35, making the total cost $2034.83. It is therefore important in selecting routes for through lines to choose those thoroughfares in which the cost of repaving will be a minimum.

## CHAPTER XI.

## CABLE WORK.

CABLES for underground electric light and power circuits are made up in single, duplex, concentric, three conductors and four conductors or more in special cases. Duplex cables are those in which two conductors are enclosed in one lead sheath side by side, while concentric cable is made up with

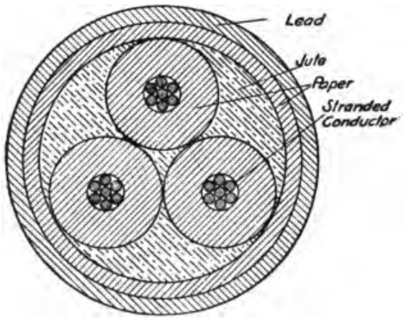



Fig. 112. High Voltage Cable Insulation.

one conductor in the center and the other outside. Three- and four-conductor cables are made with conductors side by side, as shown in Fig. 112.

**Types of Cable.** — In general, single-conductor cable is used when frequent taps are required, as in distributing mains, while concentric and other multiple conductor cables are used for through lines where taps are not made. Duplex cable has been used quite extensively in series arc systems and in single-phase taps of alternating-current systems. It

is difficult to train in manholes, as it does not bend easily in the plane of the conductors, and with paper insulation is especially susceptible to the entrance of moisture and to injury from bending at too small a radius. Duplex cable is somewhat less expensive in first cost than two single conductors with the same insulation.

Concentric cables are used in preference to duplex where the conductors are over No. 0, as the side-by-side arrangement makes a cable which it is very difficult to bend, and in the larger sizes it cannot be drawn into a standard duct. The greater facility of jointing makes the use of duplex somewhat preferable in the sizes below No. 0 B. & S. The concentric arrangement is therefore employed for large low-tension feeders and for two-wire primary feeders in some cases. This arrangement is especially advantageous with low-tension feeders, as it permits the use of a single duct for the outers of an Edison feeder of 750,000 or larger where two ducts would be required if single-conductor cables were used. This is of much importance where feeders are numerous and duct space limited, as is often the case in the larger cities.

Low-tension feeders which are added in a congested district are often run so close to other feeder ends that no additional neutral capacity is required. A concentric cable may thus constitute an entire feeder occupying but a single duct. When additional neutral capacity is needed it may be installed in the form of bare stranded cable, one duct being used for the neutral of several feeders.

Low-tension distributing mains which have three conductors of the same size should preferably be of single-conductor cable, in order to facilitate the work of making service taps. This work must be done with the lines alive, and is much more easily accomplished when one polarity may be dealt with at a time. The same is true of service cables which are

terminated in damp basements or sidewalk areas where good insulation is maintained with difficulty and where the separation of polarities is very desirable.

Two-phase and three-phase feeders from which few taps are taken are preferably of three- or four-conductor paper cables, owing to the lower cost of a single lead sheathing and of paper as compared with single-conductor cables of cambric or rubber. The use of single-conductor on the primary mains is preferable from the standpoint of the expense of jointing and separation of polarities. It is often desirable to use single-conductor cables at points where multiple-conductor feeders are connected to an overhead section, as this makes a safer installation to handle on a pole top.

Secondary cables carrying loads of 200 amperes and upward are subject to inductive action when made single conductor. The magnetic field may become strong enough to induce an appreciable difference of potential between the lead sheaths of single-conductor cables of a circuit and cause a flow of current sufficient to cause injury to the lead sheaths where they are in contact with each other. This can be prevented by the use of a jute covering over the lead sheath, though this is found objectionable in case repairs are necessary, owing to the tendency of such cables to stick in the duct. The preferable method with cables of 4/0 and smaller is to use a multiple-conductor cable. Short pieces of single conductor may be spliced into the main at the manholes where service taps are to be made to facilitate such connections. The saving in first cost due to the use of the three-conductor cable compensates partly for the expense of making the extra splices.

Transmission lines, which are usually three-phase, are almost universally of three-conductor cable with a thickness of insulation on each conductor sufficient for the voltage between phases. Another layer is placed over all three conductors in

addition to that on the separate cables, as shown in Fig. 112, to provide insulation to ground.

The type of cable selected varies according to the service in which it is to be used. All cable drawn into conduit, however, is alike in that its insulation is protected by a sheathing of lead which is designed to exclude moisture and insure permanence.

**Insulation.** — The earliest cables were insulated with rubber. The expense of this and the use of a waterproof sheath suggested the use of a wrapping of strips of oiled paper. The paper insulation proved very practical provided proper precautions were taken in making joints and in protecting the ends to exclude moisture. The difficulty of doing this under certain circumstances led to the development of insulation made of varnished cambric. This is less expensive than rubber, but more expensive than paper, and is not so susceptible to moisture at joints and terminals.

These various considerations have resulted in the use of rubber insulation where frequent taps are made on distributing mains, but not generally for through lines such as feeders and transmission lines. Varnished cambric has been used to a limited extent in place of rubber, under similar conditions. It is also used quite generally in high-tension bus-bar work inside of stations and substations. Oiled paper is used almost exclusively for feeders and transmission lines, and can be used for primary distributing mains if the joints are covered with a lead sleeve and the ends are protected by pot-heads.

Low-tension cables are provided with about $\frac{4}{32}$-inch insulation between conductors and lead in single conductor and the same amount over each conductor in a multiple-conductor cable, with no extra layer of insulation over all. This is the least which it is advisable to use for mechanical reasons and

is sufficient for any voltage up to 500 or 600. In single-conductor cables of 350,000 to 1,000,000 c.m., it is customary to provide $\frac{5}{32}$-inch paper and $\frac{6}{32}$-inch in larger cables, to provide proper strength of insulation during installation. $\frac{6}{32}$ inch is found sufficient for 2000- to 6000-volt single-conductor cables up to 4/0, while $\frac{10}{32}$ inch is required for potentials from 9000 to 13,000 volts.

TABLE VIII. — WEIGHTS AND DIAMETER OF SINGLE-CONDUCTOR, PAPER AND LEAD COVERED CABLE.

| Size B. & S. and Edison. | Thickness of paper. | Diameter in inches, over | | | Weights in lbs. per foot. | |
|---|---|---|---|---|---|---|
| | | Copper. | Paper. | Lead $\frac{4}{32}$ in. | Copper. | Total copper, paper, lead. |
| 6 | $\frac{4}{32}$ | .180 | .430 | .680 | .085 | .922 |
| 4 | $\frac{4}{32}$ | .234 | .484 | .734 | .140 | 1.069 |
| 2 | $\frac{4}{32}$ | .295 | .545 | .795 | .224 | 1.256 |
| 0 | $\frac{4}{32}$ | .378 | .628 | .878 | .338 | 1.920 |
| 00 | $\frac{4}{32}$ | .425 | .675 | .925 | .426 | 2.111 |
| 000 | $\frac{4}{32}$ | .475 | .725 | .975 | .532 | 2.326 |
| 0000 | $\frac{4}{32}$ | .524 | .774 | 1.024 | .650 | 2.551 |
| 200 | $\frac{4}{32}$ | .505 | .755 | 1.005 | .614 | 2.473 |
| 250 | $\frac{4}{32}$ | .568 | .818 | 1.068 | .790 | 2.786 |
| 300 | $\frac{5}{32}$ | .637 | .949 | 1.199 | .949 | 3.243 |
| 350 | $\frac{5}{32}$ | .680 | .992 | 1.242 | 1.092 | 3.484 |
| 400 | $\frac{5}{32}$ | .735 | 1.047 | 1.297 | 1.224 | 3.738 |
| 450 | $\frac{5}{32}$ | .777 | 1.089 | 1.339 | 1.343 | 3.949 |
| 500 | $\frac{5}{32}$ | .820 | 1.132 | 1.382 | 1.550 | 4.251 |
| 600 | $\frac{5}{32}$ | .900 | 1.212 | 1.462 | 1.874 | 4.752 |
| 750 | $\frac{5}{32}$ | 1.020 | 1.332 | 1.582 | 2.331 | 5.473 |
| 800 | $\frac{5}{32}$ | 1.037 | 1.349 | 1.599 | 2.462 | 5.642 |
| 900 | $\frac{5}{32}$ | 1.096 | 1.408 | 1.658 | 2.815 | 6.126 |
| 1000 | $\frac{5}{32}$ | 1.157 | 1.469 | 1.719 | 2.138 | 6.583 |
| 1250 | $\frac{5}{32}$ | 1.296 | 1.608 | 1.858 | 3.831 | 7.584 |
| 1500 | $\frac{6}{32}$ | 1.412 | 1.787 | 2.037 | 4.681 | 8.969 |
| 2000 | $\frac{6}{32}$ | 1.652 | 2.027 | 2.277 | 6.237 | 11.077 |
| 2500 | $\frac{7}{32}$ | 1.848 | 2.285 | 2.535 | 7.674 | 13.221 |

The thickness of insulation, weight of copper, paper and lead sheath and over-all diameters of various sizes of single-conductor paper-insulated cables are presented in Table VIII. It will be noted that the diameter of 600,000 c.m. cable being 1.462 inches, this is the maximum size of cable of which two can be drawn into a $3\frac{1}{2}$-inch tile duct without undue strain.

The diameter of three-conductor cables of various insulations is given in Table IX. The largest diameter in each column is the largest cable which can be drawn into a standard $3\frac{1}{2}$-inch duct.

TABLE IX. — APPROXIMATE OUTSIDE DIAMETERS OF ELECTRIC LIGHT AND POWER CABLES. THREE CONDUCTOR ($\frac{1}{8}$ Lead throughout).

| Size. | Insulation thickness on each conductor and over bunch respectively equal to — | | | | | | | Size. |
|---|---|---|---|---|---|---|---|---|
| | $\frac{3}{32}$ $\frac{1}{64}$ | $\frac{3}{32}$ $\frac{3}{32}$ | $\frac{4}{32}$ $\frac{4}{32}$ | $\frac{5}{32}$ $\frac{5}{32}$ | $\frac{6}{32}$ $\frac{6}{32}$ | $\frac{7}{32}$ $\frac{7}{32}$ | $\frac{8}{32}$ $\frac{8}{32}$ | |
| | Diam. | Diam. | Diam. | Diam. | Diam. | Diam. | Diam. | |
| 6 | 1117 | 1242 | 1437 | 1637 | 1832 | 2032 | 2227 | 6 |
| 5 | 1164 | 1289 | 1485 | 1684 | 1880 | 2079 | 2275 | 5 |
| 4 | 1218 | 1343 | 1539 | 1738 | 1934 | 2133 | 2329 | 4 |
| 3 | 1281 | 1406 | 1602 | 1801 | 1997 | 2196 | 2392 | 3 |
| 2 | 1352 | 1477 | 1673 | 1872 | 2068 | 2267 | 2463 | 2 |
| 1 | 1436 | 1561 | 1757 | 1956 | 2152 | 2351 | 2547 | 1 |
| 0 | 1525 | 1650 | 1846 | 2045 | 2241 | 2440 | 2636 | 0 |
| 00 | 1624 | 1749 | 1945 | 2144 | 2340 | 2539 | 2735 | 00 |
| 000 | 1736 | 1861 | 2057 | 2256 | 2452 | 2651 | ...... | 000 |
| 0000 | 1860 | 1985 | 2180 | 2380 | 2575 | ...... | ...... | 0000 |
| 250,000 | 1961 | 2086 | 2282 | 2481 | 2677 | ...... | ...... | 250,000 |
| 300,000 | 2080 | 2205 | 2401 | 2600 | ...... | ...... | ...... | 300,000 |
| 350,000 | 2188 | 2313 | 2509 | 2708 | ...... | ...... | ...... | 350,000 |
| 400,000 | 2289 | 2414 | 2610 | ...... | ...... | ...... | ...... | 400,000 |
| 450,000 | 2387 | 2512 | 2708 | ...... | ...... | ...... | ...... | 450,000 |
| 500,000 | 2479 | 2604 | ...... | ...... | ...... | ...... | ...... | 500,000 |

The insulation provided in various cables designed for different voltages in some of the large transmission systems is shown in Table X. It will be noted that the thickness of insulation varies from 67 mils per 1000 volts between conductors at 6600 volts to 22 mils at 25,000 and from 52 mils per 1000 volts between conductor and ground at 6600 volts to 16 mils at 25,000 volts. These differences are due in part to differences of opinion as to what factor of safety would be used in the design of high-potential cables. The lower values of thickness are used on the higher voltages because the thickness required does not vary directly with the voltage.

TABLE X.

| Company. | Line voltage. | Kinds of insulation. | Thickness of insulation in thousandths of an inch | | | |
|---|---|---|---|---|---|---|
| | | | Between conductors. | Between conductors and ground. | Per 100 volts. | |
| | | | | | Between conductors. | Between conductors and ground. |
| N.Y. Edison Co... | 6,600 | Paper | 312 | 312 | 47 | 47 |
| N.Y. Metropolitan | 6,600 | " | 436 | 343 | 67 | 52 |
| Commonwealth Edison......... | 9,000 | " | 406 | 383 | 44 | 38 |
| N.Y. Sub. Co..... | 11,000 | " | 436 | 468 | 40 | 43 |
| N.Y. Manhattan.. | 11,000 | " | 436 | 436 | 40 | 40 |
| Buffalo Niagara L. | 11,000 | " | 406 | 406 | 37 | 37 |
| Milwaukee........ | 15,000 | " | 500 | 437 | 33 | 29 |
| St. Paul.......... | 25,000 | " | 562 | 484 | 22 | 19 |
| Montreal......... | 25,000 | " | 562 | 406 | 22 | 16 |

**Current-carrying Capacity.** — In low-tension work and in some large transmission systems it is important to select cables with reference to the maximum safe current-carrying capacity as nearly as possible.

The carrying capacity of lead-sheathed cables in conduit is dependent upon (*a*) the size and number of cables in the conduit, (*b*) the radiating capacity of the conduit and cable, and (*c*) the ability of the insulation to withstand high temperatures.

Stating it in another way, the carrying capacity of a cable is fixed by the maximum temperature at which it is safe to operate the insulation. The size and number of cables and their load fix the amount of energy released in the conduit line in the form of heat, while the resulting temperature is fixed by the radiating capacity of the cable insulation and the duct system. It is apparent that the ducts which are inside and have no direct contact with the concrete casing of the duct line will run warmer than those around the edge. Likewise it is natural that the inner conductors of concentric cables should run hotter than those next to the sheath. The

exact effect of such relations has been studied by Fisher in connection with the Niagara Falls Power Company's system, by Ferguson in the Chicago central station system and others. In general the result of such tests indicated that with a nine-duct line the rating of a cable should be reduced to about 85 per cent of its capacity when in a four-duct line, while in a sixteen-duct line it should be reduced to 60 per cent. This is true, however, only when the ducts are full of working cables.

The carrying capacity of a multiple-conductor cable is reduced because of the greater amount of energy which must be dissipated per foot of cable. The Standard Underground Cable Company is authority for the statement that duplex cable has 87 per cent of the carrying capacity of single conductor, concentric cable 78 per cent and three conductor 75 per cent. The heat-conducting power of rubber is somewhat better than that of oiled paper, and a given thickness of rubber insulation may therefore be relied upon to convey more heat away from the conductor than the same amount of paper. However, the maximum temperature at which rubber should be operated is about 65 degrees C., and the ampere load on such a cable should not be such as to run the temperature beyond this point. The temperature of paper cables may at times be pushed above this figure, but if operated continuously above 85 degrees C. the insulating value of the paper will be injured.

The carrying capacity of certain of the more common size of single-conductor lead cables and the watts per foot at 65 degrees C. are given in the following table:

| Size...... | 6 | 4 | 2 | 1 | 0 | 0000 | 300 | 400 | 500 | 750 | 1000 | 1500 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Current... | 64 | 91 | 125 | 146 | 168 | 260 | 323 | 390 | 450 | 583 | 695 | 895 | 1085 |
| Watts per foot.... | 1.85 | 2.31 | 2.77 | 3.0 | 3.23 | 3.92 | 4.22 | 4.61 | 4.91 | 5.46 | 5.86 | 6.49 | 7.09 |

Tests reported by Ferguson in his paper before the International Electrical Congress at St. Louis in 1904 furnish very useful data as to the temperatures attained in paper-insulated cables laid in underground conduits. Fig. 113 shows the rise in temperature experienced by a 1,000,000 c.m. single-conductor cable, in tile duct and in air, when carrying loads from 800 to 1900 amperes. It will be noted that at a load of 1000 amperes the rise of temperature of the cable in the air is

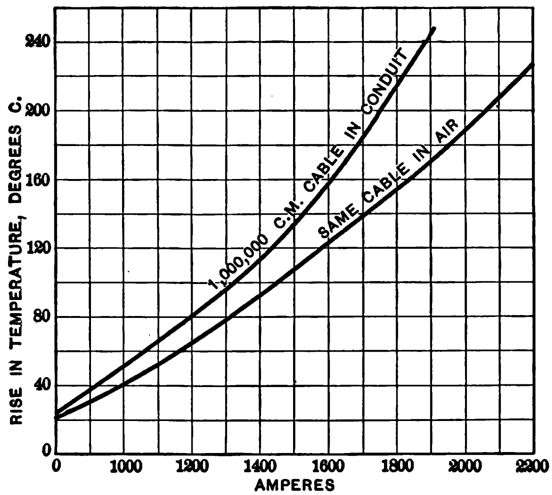



Fig. 113. Heating of Single Conductor Cable.

41 degrees C., while in conduit it is about 10 degrees C. higher.

The results represented by the curve in Fig. 114 show the rate of rise of temperature in a two-conductor concentric cable of 1,000,000 c.m. in each conductor when it is carrying 1000 amperes. It is apparent from the curves that the temperature of the outer conductor is practically the same as that of the single-conductor cable of the same section in air, but that the inner conductor runs hotter. The rate of rise is such that

the ultimate elevation of 40 per cent in the outer conductor is reached in about $2\frac{1}{2}$ hours, 70 per cent of this rise having occurred in the first hour. Overloads of short duration may therefore be carried safely. Data for a three-conductor cable of 4/0 in conduits are given in Fig. 115 for various ampere loads. This cable was loaded with an equal current in each conductor, and it is apparent that with equivalent current

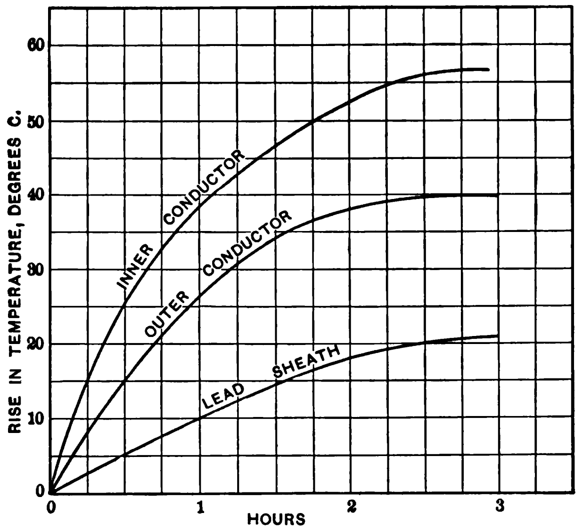



Fig. 114. Heating of Concentric Cable.

densities this cable runs cooler than the 1,000,000 c.m. cable. This is due to the fact that the radiating surface of the three-conductor cable is over 60 per cent greater than that of the single-conductor 1,000,000 c.m. cable.

The load on a cable is preferably expressed in watts per duct foot, as the heating of cable and air is directly proportional to this quantity.

The resistance of a 1,000,000 c.m. cable being .0000124 ohm per foot at 50 degrees C., the energy loss, $C^2R$, in a single-

conductor cable at 1000 amperes is 1000 × 1000 × .0000124 = 12.4 watts. Likewise in a 1,000,000 c.m. concentric cable the loss is 24.8 watts per foot. In a three-conductor 4/0 cable, with 200 amperes current on each conductor, the resistance per foot being .00006, the loss per foot of cable is 3 × 200 × 200 × .00006 = 7.2 watts. With smaller conductors the

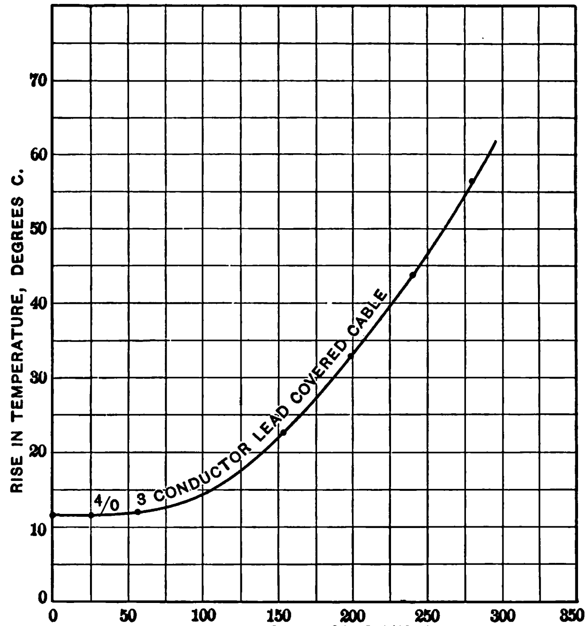



Fig. 115. Heating of Three-conductor Cable.

energy loss is less for a given current density, and the surface of radiation not decreasing proportionately, the current density may be run above 1 ampere per 1000 c.m.

**Selection of Ducts.** — In placing cable in the duct system a uniform method of selecting ducts should be followed as far as possible. The cable of a through line should occupy the same relative position throughout its course as far as this is

possible. Cables used in local distribution should be given a uniform place in the duct system, preferably in the top row, so that handholes can be built between manholes for service laterals without sinking them below the top row of ducts. The lower ducts are thus left vacant for through lines which may be trained through the manhole below junction boxes, fuse boxes, etc., which it is desirable to mount on the walls of the manholes.

Ducts should be selected for through lines so that they may be trained where the line changes direction with the least interlacing with other cables. Lack of attention to this detail may result in a tangled condition which increases the danger to other cables if one burns out, and greatly impedes any repair or reconstruction work which may become necessary.

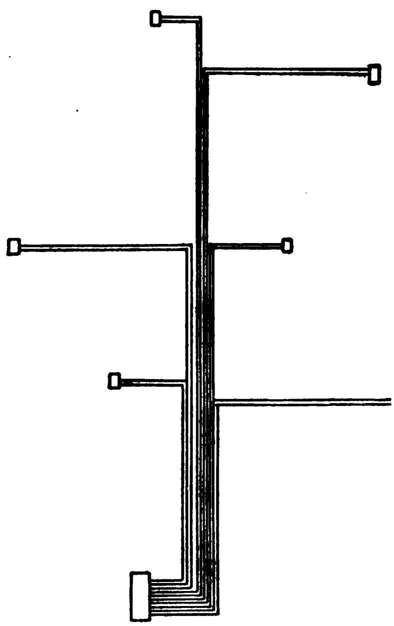


Fig. 116. Lines Routed in Same Duct Lines.

**Routing of Lines.** — Through lines should be so routed as to utilize duct lines to the best advantage. When a duct is taken for a through line on a given street it should follow that route as far as possible, as the corresponding duct on the remainder of the street is blocked for use on through lines going elsewhere.

The safety of the service is better assured if transmission lines are separated as much as possible. This can be done

by routing lines running to the same substation through different conduits. The two arrangements shown in Figs. 116 and 117 supply a group of six substations with duplicate lines to each. In Fig. 116 the amount of duct line is a minimum but the risk is a maximum, while in Fig. 117 ducts in the

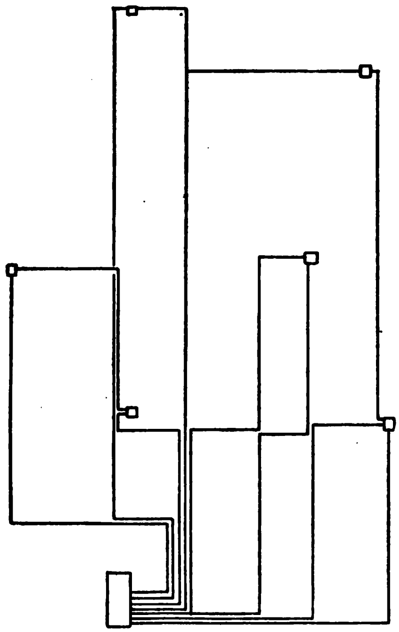


Fig. 117. Lines Routed in Different Duct Lines.

distributing conduit lines on other streets are used with the maximum of protection from interruption of service due to cable trouble.

**Installation of Cable.** — Cables are drawn into ducts by means of a line attached to a source of power. This line is put through the duct by the use of detachable rods of wood about three feet long and 1 inch in diameter, which are pushed

into the duct as they are joined together. They are then drawn through with the pulling line attached and disjointed as they come through.

When the cable pulling line is ready for use, it is run over pulley wheels out of the manhole and to the source of power. The reel of cable is set up on an iron bar so that it will revolve and pay out cable as it is drawn in. Enough men are placed at the reel and in the manhole to guide the cable into the duct and prevent its sheath being injured as it passes through the manhole opening.

Power is supplied for pulling in various ways. With short runs and small cable a few men can draw the cable in. With runs of 300 to 500 feet the most general power is a capstan manned by 6 or 8 laborers. In the large cities where many heavy cables are being pulled, in long runs, an automobile truck has been used to advantage, the speed being reduced by block and tackle and by running the truck at slow speed. This permits of work being done more rapidly than with a capstan. The cables are secured to the pulling line by baring the copper and making a secure mechanical connection or by means of patent cable grips, which are more quickly attached and removed, and save considerable time.

Where several cables are to be drawn into one duct they should be installed simultaneously by securing them to one line, as if it is attempted to pull them separately the duct cannot be utilized as fully as it should. Five single-conductor cables of any size up to number 4 can be drawn into a square $3\frac{1}{2}$-inch duct without danger of injury.

Small cable is usually put up on reels and cut to fit as it is drawn in, but a length of about 400 feet of three-conductor high-voltage cable or of 1,000,000 c.m. feeder cable, fills a reel, and it is therefore usual to order such cable in specified lengths. The distance from center to center of manholes plus the amount needed for training around the walls of the manhole

and splicing is the length to be ordered. The reels are marked for delivery at certain street intersections and with the length of cable which they contain. It is important that such lengths be determined within a few feet, as all short ends cut off by the jointer are of value only as junk, and may represent a considerable sum of money on a large job, where the cable costs from \$1.00 to \$2.00 per foot

**Training through Manholes.** — The training of cable through manholes must be done carefully to avoid sharp bends, tangled relations with other cables and possibility of injury due to exposure to workmen's shoes while entering or leaving the manhole. It is customary to support cables in some localities on iron racks hung on the brickwork of the walls. In other cases brickwork shelves are built around the walls, on which the cable is laid. In some large systems the important cables are laid in split tile ducts carried on shelves around the sides of the manhole. The tile is made in short lengths, with curved pieces suitable for covering the bends, and being in two parts is easily applied after the cable is drawn in and jointed. The tile serves to protect adjacent cable from injury in case a transmission cable fails and also from possible injury from mechanical interference during the progress of work on other cables in the manhole.

Where high-voltage cable is carried through manholes on iron racks without protection, the failure of the cable at one point is apt to charge the lead sheath and cause it to be damaged in adjacent manholes where the current attempts to pass from the lead to ground through the iron racks. It is usual to protect high-tension cables in manholes to prevent the communication of trouble to other cables than the one which fails. This is done by wrapping them with asbestos tape or some similar fireproofing material, or by the use of split tile or brick shelving as described above. The tile is

the most expensive, but forms the best protection where there is large station capacity back of the short circuit. Where lines are carrying loads of 1000 kilowatts or more of important light and power service the extra cost of the tile protection is amply justified.

With paper cables particularly and with other cables as a rule, the radius of bends must not be made too small. The shape of the manhole walls and the manner of bringing the ducts into the walls should be designed with this in view. Generally, the radius of a bend should exceed 8 or 10 times the diameter of the cable. This is one of the chief limitations in the use of heavy concentric and multiple-conductor cables whose diameter is such that they could be trained through manholes with difficulty if larger sizes were attempted. In case of changes which necessitate the withdrawal of cable, the larger sizes may be ruined in passing over the idler wheels as the cable emerges from the manhole, due to the necessarily small radius at which it is bent. It is theretore necessary to devise special means of pulling cable out without subjecting it to strain in passing over the idlers as is usually done with smaller cables in some cases.

**Cable Jointing.** — As soon as the lengths are drawn in the ends should be sealed, to exclude moisture, unless they are to be jointed at once. The work of jointing requires the services of an expert, especially with high-tension paper cables. In jointing single-conductor cables, the lead sheath is removed five or six inches back from the end of each piece of cable and enough of the copper bared to permit a good soldered connection being made as in any other cable of similar section. After soldering, the bare parts are wrapped with tape of the same material as the insulation until the equivalent of the cable insulation has been applied. A lead sleeve which has previously been slipped back over one of the cables is now

wiped on to the two cables so as to enclose the joint. The air spaces around the joint are then filled by pouring hot insulating compound into a small hole in one end of the sleeve until it does not settle down further. A similar hole should be left open in the other end of the sleeve to allow air to escape

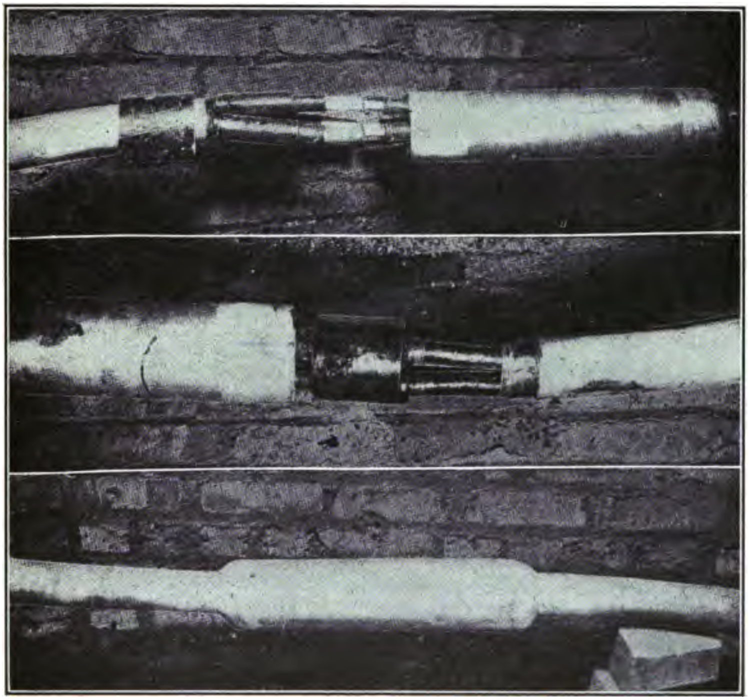


Fig. 118. Process of Making Joint.

easily while pouring the compound. The openings in the lead sleeve are then closed by soldering, thus sealing the joint from moisture. The joint should be allowed to cool before it is moved, so that the relative positions of the conductor and insulation may not be disturbed. The various operations for a three-conductor cable are illustrated in Fig. 118.

In jointing three-conductor cables the lead must be cut away further back to facilitate the separation of the conductors while the tape is being applied. If any sign of moisture appears in the ends of the cable, the end of the cable should be cut back until it is eliminated. If this cannot be done without removing too much, it may be necessary to drive it off by heating the cable with a blow torch several feet back from the end. The presence of slight amounts of moisture should be guarded against by pouring hot compound over the bared ends. The compound should be hot enough to boil water, but not so hot as to char a piece of paper. In making joints for voltages of 6600 and higher some special precautions are necessary. It is very important that as little air remain in the taping as possible. If paper tape is used each layer should have compound poured over it before the next is applied. Some cable manufacturers prefer to use a cotton tape for this purpose on account of its absorbent qualities. Some of the most successful cable systems have been jointed with specially prepared paper tubes. These are slipped back over the conductors before they are joined together and are later secured in place over the taped joint, thus making a rigid mechanical separation between polarities. A large tube is slipped over all three conductors as further insulation to ground. The lead sleeve must be large enough to slip over the taped joints, and in three-conductor cable the space taken by the joints is such that the diameter of the sleeve must be from 1 inch to 1½ inches more than that of the cable. With single-conductor cable ½ inch to ¾ inch more is usually enough. Where a tap is to be taken off, the sleeve may be arranged at right angles in the form of a T, or at a tangent. The T joint is usually difficult to dispose of on the manhole wall without straining the sleeve, while the other form may be trained along with the cable to which it is tapped.

Where single-conductor cables are joined to multiple conductor, the joint is made in a similar manner, the single conductor cables being flared out slightly, to insure proper separation and to permit the proper wiping of the sleeve.

Such joints are more difficult to make than straightaway splices and require considerable skill. The jointer requires the services of a helper in preparing the lead sleeves, heating solder and compound and guarding the entrance to the manhole. A three-conductor high-tension joint in a paper cable usually requires about 4 to 5 hours to complete, two joints a day being a fair rate of progress in such work. Single-conductor and low-tension cables do not require as long a time.

Fig. 119. Porcelain Pot-head.

**Pole Terminals.** — In most primary distributing systems in which part of the lines are underground, there are connections made between underground and overhead lines. It is usual to run feeders and important mains underground for some distance from the station in large cities, and then connect with overhead lines in the more scattered areas.

Where alley distribution is general the main lines are placed underground on streets and the local distributing taps taken off to overhead lines in alleys. In other locations lines must be carried underground across a boulevard, railroad or stream. This class of distribution was for many years very troublesome because of the difficulty of properly caring for the cable ends which are brought up the pole to the overhead lines.

Plain joints made by stripping the lead back a few inches and covering with tape and compound were succeeded by wiped lead sleeves filled with compound and left open at the end

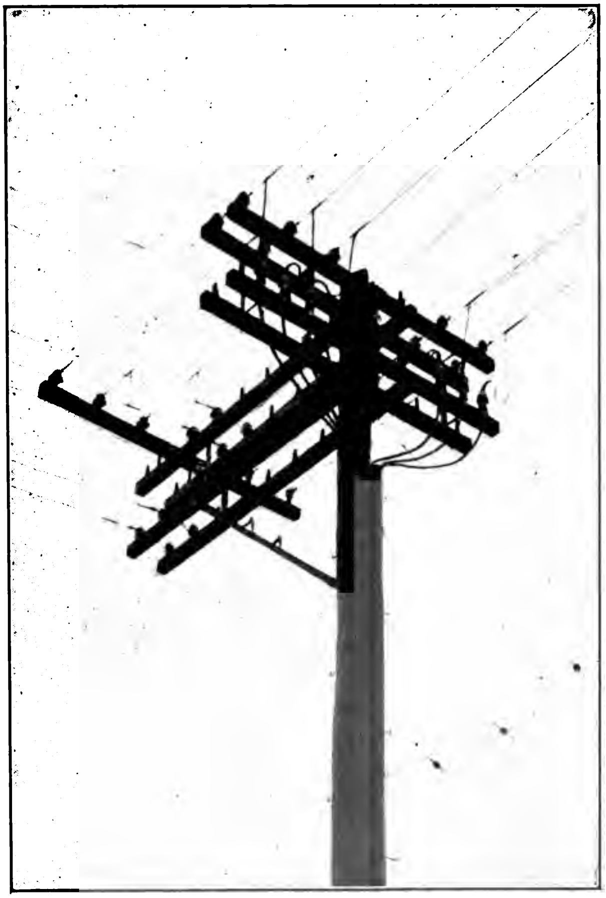


Fig. 120. Installation of Porcelain Pot-heads.

where the line wire came out. In some cases the joints were protected by enclosing them in wooden boxings. All of these various forms were susceptible to the action of sun and rain

and were sooner or later located by lightning flashes or otherwise as the weak spots in the line. In recent years many of the large distributing systems have been equipped with a porcelain pot-head devised by the authors to meet such conditions as they arose in Chicago. The device as designed for a single-conductor cable is illustrated in detail in Fig. 119, and one method of installing them is shown in Fig. 120.

Fig. 121. Porcelain Pot-head for Three-conductor Cable.

The insulation is thoroughly sealed from moisture by filling the porcelain sleeve with hot compound. The cap being similar to an insulator sheds all water when properly taped, and may be safely handled by a lineman when the circuit is alive at any pressure up to 5000 volts. The metal connectors

provide means for opening or closing the circuit with ease for repair or alteration work when desired. Other forms have been devised for multiple-conductor cables, one of which is shown in Fig. 121. In this form the pot is of cast iron, only the tubes which are set into the cover and the caps being of porcelain; at voltages above 2300 the caps are provided with double petticoats.

**Transformers and Junction Boxes.** — The arrangement of transformers, fuse boxes, junction boxes and similar accessories in manholes should be worked out with care and foresight. Such apparatus should not be so placed in manholes

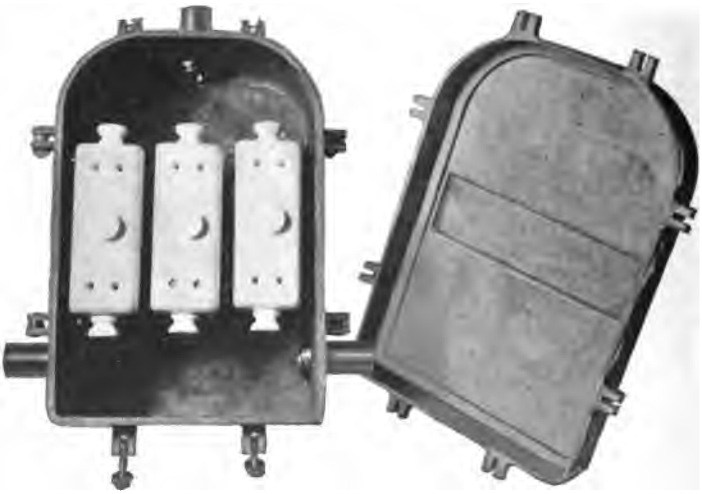


Fig. 122. High-voltage Junction Box.

as to obstruct the introduction of additional cables at a later date or to make a neat and orderly arrangement of cables impossible. It is first of all important that manholes in which the larger pieces of apparatus such as transformers or low-tension junction boxes are placed should be of ample size to accommodate them properly.

Low-tension junction boxes for use in manholes are of two types, one of which is mounted on the wall in a vertical position, while the other is placed horizontally in the roof of the manhole with a separate cover, so that it is accessible for replacing fuses or cleaning contacts above ground. The former type is perhaps the better as regards the training of cables, as they may be kept in order on the walls of the manhole. The ability to do maintenance work on the surface is of some

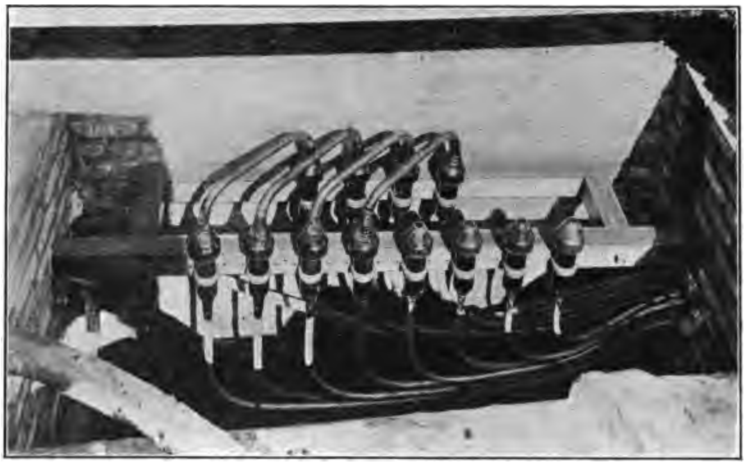


Fig. 123. Emergency Disconnectives in Manhole.

advantage in less congested districts where the traffic is light and the drainage of manholes not perfect, but in a busy street it is preferable to be able to do this work in the manhole where it is not interfered with by passing wagons or crowds of curious observers.

In alternating-current systems, space is required for primary junction boxes, or fuse boxes, and in some manholes for transformers. In a primary cable system in which both feeders and branches are underground, it is necessary to have means by which branches may be disconnected without shutting the

whole circuit down at times when a transformer is to be connected or when an emergency exists. Disconnectives must therefore be provided in some form for this purpose. It is also desirable in an emergency to have means readily available by which parts of any circuit may be cut over to another circuit through suitable disconnectives.

Fuse boxes with copper connections have very commonly been applied to this work. A three-conductor box of this character which may be used as a disconnective is shown in Fig. 122. The three-conductor cable of the main line runs through one end of the box and the tap joints are made inside the box. The parts of the cable from which the lead has been removed are then sealed in from moisture by partially filling the box with hot compound. The box is mounted horizontally and has a deep overlapping cover which prevents the entrance of water in case it is submerged.

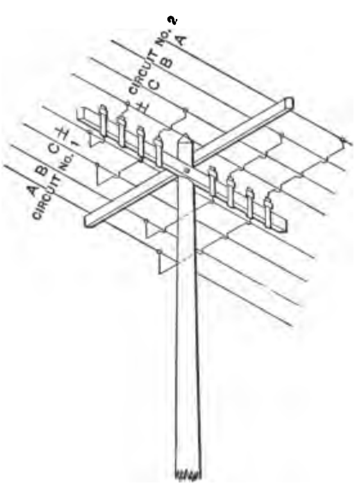


Fig. 124. Emergency Disconnectives on Overhead Circuits.

When single-conductor cable is employed, single boxes are used.

The porcelain pot-head above described has been found convenient for this purpose also, in manholes. A pot-head is placed on the end of each section of cable, and the connection between caps is made by a piece of rubber-insulated stranded wire suitable for 10,000 volts. In some respects such an installation is safer to operate than one made with iron boxes. It is submersion proof if well made, as the caps of the pot-heads have suffi-

cient overlap to prevent water from rising to the live metal parts. Installations of this class in Chicago have been submerged during heavy rains without the slightest interruption of service. Such an installation is illustrated in Fig. 123 and accomplishes the same purpose as the overhead arrangement shown in Fig. 124.

## CHAPTER XII.

### DISTRIBUTION ECONOMICS.

DISTRIBUTION engineering involves various economic problems which are of importance to the commercial success of a central station property. These problems often involve conflicting conditions between which a minimum may be found. Others are concerned with the practical conditions of life which influence the financial success of the enterprise.

The determination of the most economical sizes of conductors for feeders, mains and transmission lines is of great importance, since the distributing equipment forms a large proportion of the investment and net earnings are affected by its design to a large extent.

In the selection of the size of a conductor for a feeder or transmission line, the energy loss tends to diminish as the size of the conductor is increased, and *vice versa*. The generating capacity required to supply the energy loss also decreases as the size of the conductor is increased.

Hence there is a point at which the sum of the fixed charges on conductor, fixed charges on generating capacity, and the value of energy loss is a minimum. The size of the conductor with which this condition of minimum annual cost is realized, is that which it is the most economical to employ.

The fixed charges are composed of interest on the capital, depreciation of the physical property, taxes and insurance. These quantities are necessarily computed at different rates, depending upon the character of the different parts of the property.

The energy loss involves the consumption of fuel and is computed at the cost of energy as delivered at the switchboard from which the circuit is supplied.

In calculating interest the investment figure should include the cost of the conductor with its insulation and any other expense which is proportional to its cross-section.

Interest should be figured at the rate paid on the bonded debt or at the current rates for the use of money for similar public service utilities if there are no bonds.

**Depreciation.** — Depreciation should be based upon the working life of the apparatus and conductors, allowing for the possibility of changes in the state of the art, and the probable second-hand value of the equipment at the end of its period of service.

The rate of depreciation is stated as a percentage and varies with the different kinds of equipment. For instance, if the working life of a lead cable is found by experience to be ten years, the depreciation would be ten per cent annually, less the junk value of the copper and lead at the end of the ten-year period. If the junk value were 50 per cent of the original cost of the cable, the depreciation would be 5 per cent, or if the junk value were 25 per cent, the depreciation would be $\frac{1}{10}$ of 75 per cent, or 7.5 per cent annually.

The rate of figuring depreciation is necessarily a matter of judgment based on the best experience available and is therefore apt to vary somewhat according to the purpose for which the figures are to be used.

The continued evolution of the art of manufacturing electrical apparatus and the rapid growth of the central station industry have caused the abandonment of the older types long before they were worn out, in order to get the more efficient newer ones. In many cases, this has resulted in much higher rates of depreciation than would have prevailed had

the machinery been able to serve out its normal life. This form of depreciation is sometimes called obsolescence.

Generating machinery has, however, reached a reasonably high state of perfection and can be counted on at the present time to serve during the life of its wearing parts and its insulation, unless it is so coupled to a prime mover which becomes obsolete that it cannot be used with the new form of prime mover, as was the case with steam turbines.

Where the prime mover is a water wheel the life of the unit as a whole is more likely to be realized in actual service, as the possibilities of improvement in hydraulic equipment seem to be more limited than with steam machinery, and the size of the unit is usually made as large at the start as the water supply will justify.

Managers of large properties who have been successful in carrying their equipment through the evolution of the art with a rapid growth are therefore apt to consider depreciation at a higher rate than those who are starting with new and modern equipments from the ground up. The more experienced figure depreciation on generating equipment at about 6 to 7 per cent and on buildings at 3 per cent, with an average of about 5 per cent on the whole plant.

It is of course assumed in the above figures that the repair and renewal account will stand from year to year all necessary maintenance costs which are required to keep the plant in economical operating condition and not allow the property to run down.

The rate on a hydraulic development might be considered somewhat lower because of the more stable character of the equipment and the smaller proportion of the total investment which is subject to wear and tear. The damage from floods must be reckoned with, however, and this sometimes reduces the life of the investment very greatly. In distributing lines the depreciation is higher from the nature of the equipment,

but the junk value is a much larger proportion of the original cost than is the case with station apparatus.

Weatherproof wire consists of about 80 per cent copper and 20 per cent insulation in the sizes ordinarily used for feeders. There is no depreciation on the copper except the labor of replacing it at intervals of ten to fifteen years when the insulation is worn out. The increase in the value of copper with advancing years tends to offset the loss on the insulation, so that at best it is an uncertain quantity. It is conservative, however, to figure 10 per cent on the 20 per cent of insulation or 2 per cent and 1 per cent for the labor of replacing, making a total of 3 per cent of the original cost of the wire. Poles have a life of about 15 years, with little salvage value. Other material must be replaced at intervals of five to ten years. The average rate for overhead lines may therefore be taken at 6 per cent with alternating-current systems and 4 to 5 per cent with low-tension systems.

The life of lead-sheathed paper or rubber cables is as yet indeterminate, but there is good reason to believe that these may be serviceable for perhaps fifteen years. The junk value is comparatively high, as the copper is a large part of the original cost, and the lead sheath constitutes a considerable percentage of the cross-section of the cable. It is therefore fair to estimate the depreciation on lead-sheathed cables at 3 per cent for cables of 4/0 and larger and at 5 per cent for the smaller sizes.

In a growing system the replacement of feeders due to the expansion of the load results in more rapid depreciation than is experienced in a system where the feeder conductors remain undisturbed until they are too far gone to be of further service.

**Summary of Fixed Charges.** — The usual rate of interest on bonds issued for public utilities is 5 per cent. Taxes and insurance vary directly as the amount invested, and they

must be considered as fixed charges of the same class as interest and depreciation. They vary somewhat with the locality, but are usually from 1.5 to 2 per cent. The total fixed charges on station equipment may therefore be considered as 5 per cent interest, 5 per cent depreciation, and 2 per cent taxes and insurance, a total of 12 per cent.

In estimating the value of generating capacity required to deliver the loss at maximum load, the cost of boilers, prime movers and generators should be included, as all are affected. This cost varies greatly in different plants, depending upon the size and character of the equipment. In engine-driven stations of less than 1000 K.W. the value of this equipment runs from $125 to $150 per kilowatt, while in turbine plants this cost is reduced to $90 or $100 per kilowatt. In turbine plants of 10,000 K.W. and upward the investment exclusive of buildings and real estate is as low as $70 in some cases.

In direct-current plants which generate at the distributing voltage, the generators must be wound to deliver the pressure required by the longer feeders. The shorter feeders may therefore be designed to carry the load with reference to heating only, as nothing can be saved in generating capacity by using larger conductors. The value of generating capacity may therefore be ignored in selecting the size of such feeders.

The total fixed charges on underground cable and conduit work may be taken at 5 per cent interest, 4 per cent depreciation and 1 per cent taxes, a total of 10 per cent Similarly the total rate on the average overhead system should be taken at 12 per cent.

Line transformers have an average life of 12 to 15 years, the junk value being about 20 per cent of the original cost, making the rate of depreciation about 6 per cent. These may therefore be included as a part of the overhead distributing system in figuring the fixed charges, if desired.

**General Equation.** — The investment in conductors varies inversely as their resistance per 1000 feet; the investment in generating capacity and the value of the energy loss vary directly as the resistance per 1000 feet. It is therefore possible to establish an algebraic equation having each of three elements of annual cost expressed in terms of a common variable, $R$, the resistance per 1000 feet of conductor:

$$Y = \frac{a}{R} + bR + cR.$$

Such an expression is possible since the cost of insulation varies approximately with the size of the conductor, and the pole-line or conduit-line investment is practically the same for any one of several adjacent sizes of wire or cable and is therefore eliminated from the equation.

**Fixed Charges on Conductors.** — The value of the conductors composing a circuit is directly proportional to their size and inversely to their resistance when the conductors are bare or insulated for overhead construction. With lead-sheathed cable the cost is not directly proportional, except when a few adjacent sizes are considered separately in comparison with each other.

For bare wire the product of weight per 1000 feet by resistance per 1000 feet for all sizes is $WR = 32$, while with weatherproof insulation it is $WR = 38$ for the sizes No. 4 to No. 0, or 36 for sizes from 2/0 to 350,000 c.m. The value of 1000 feet of conductor at 15 cents per pound is therefore $.15\,W$ dollars. Hence when $W = \frac{38}{R}$, the cost per conductor of a circuit $L$ thousand feet long is $\frac{.15 \times 38\,L}{R}$ dollars.

With fixed charges at 9 per cent this element of annual cost is $A = \frac{.09 \times .15 \times 38\,L}{R} = \frac{.513\,L}{R}$ dollars per year per

conductor. With underground conductors the value of insulation and lead sheath is a large proportion of the cost of the smaller sizes of cable, and a change in the size of the copper conductor does not make a proportionate change in the cost of the cable.

Table XI gives the cost per 1000 circular mils of various sizes of single- and three-conductor lead-sheathed cables for low-tension work and for ordinary primary distributing voltages.

The resistance of a mil foot of copper at ordinary temperatures being about 10.4 ohms, this is also the resistance of 1000 circular mils of conductor 1000 feet long. If $R$ is resistance per 1000 feet and $M$ is the number of thousands of circular mils, the cost of a single-conductor cable is $M$ times the cost per 1000 circular mils. $M = \frac{10.4}{R}$ and the cost of the cable is $\frac{L \times 10.4 \times P}{R}$, where $P$ is the price per 1000 circular mils and $L$ is the number of thousands of feet.

For single-conductor low-tension cable the value of $P$ in Table XI averages \$1.20 for cables from 2/0 to 500,000 c.m. and the value of each conductor is $\frac{10.4 \times 1.2\,L}{R} = \frac{12.48\,L}{R}$. With fixed charges assumed at 9 per cent, the annual conductor cost is $a = \frac{.09 \times 12.48\,L}{R} = \frac{1.12\,L}{R}$ per conductor. In applying this, if the most economical size proves to be below or above the sizes for which the cost was assumed, the figure should be corrected, using the price per 1000 c.m. corresponding to the size which seems on the first approximation to be the most economical. In this way the most economical size may be determined on the second determination if the first seems to have been based on false premises.

With three-conductor cables the cost per 1000 circular mils

in Table XI is based on the total cross-section of the three conductors. In this case the cost of the cable is $\frac{3 \times 10.4\,PL}{R}$ and $a = \frac{0.09 \times 3 \times 10.4\,PL}{R} = \frac{2.8\,PL}{R}$.

Thus the value of $a$ may be derived for different kinds of cable and at various values of copper, lead and insulation. It must be borne in mind that these values are for a single cable. Where a circuit is composed of more than one cable, this must be taken into account in figuring the total annual cost for the circuit. That is, for a two-wire circuit the value of $a$ is doubled and for three cables it is tripled.

**Fixed Charges on Generating Equipment.** — Where conditions are such that a saving in generator capacity could be made or some capacity released for commercial load by the use of larger conductors, the fixed charges on generating equipment should be considered one of the elements of annual cost of operating a circuit. This is usually the case where alternating current is distributed through potential regulators or through substation transforming apparatus, which converts the feeder loss into a load on the armature of the generator.

Where the loss is represented by the range of voltage of the generator fields, a saving in generating capacity cannot always be realized, as operating conditions usually necessitate a range of 10 to 15 per cent in the generator fields, which proportionately reduces the ampere rating of the armature for a given rated capacity.

The station capacity required to supply the energy loss at the time of the annual maximum load is $\frac{C^2RL}{1000}$ K.W. This includes only the steam and electrical equipment in a steam station. The real estate, building and accessories are not usually sufficiently affected to require their consideration as an element of cost.

In a hydraulic development, the value of generator and water wheels is the only part affected materially. The value of station capacity required to supply the loss on a feeder when the cost is \$100 per kilowatt is $\frac{100 \times C^2RL}{1000}$ and the fixed charges at 12 per cent are $b = .12 \times .1\ C^2RL = .012\ C^2RL$ dollars per conductor.

**Energy Loss.** — The loss of energy on a circuit during a year is dependent upon the variation of load from hour to hour and from day to day throughout the year. The loss for any hour may be considered as $C^2R$, when $C$ is the average value of the current during that hour.

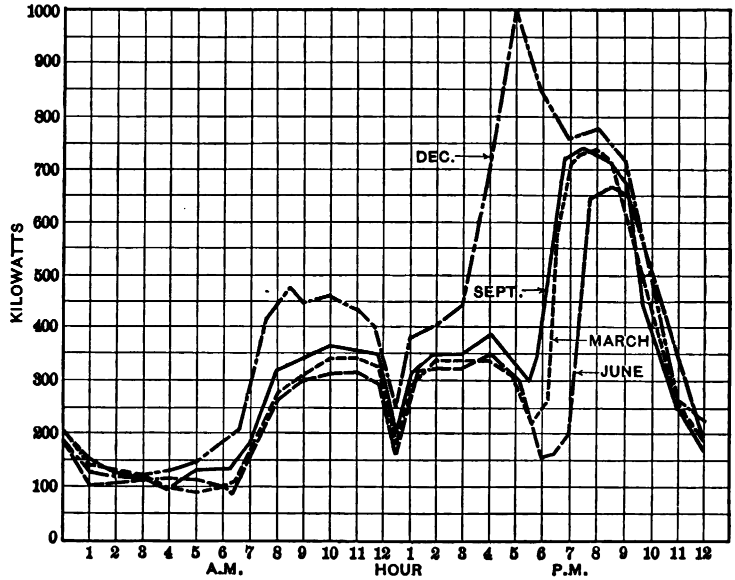



Fig. 125. Lighting Load Diagrams.

The variation from hour to hour in general distribution work changes from day to day, depending upon the habits of the people who use the electricity, and from season to season

as the length of the daylight hours changes. During the winter months the use of light begins in the late afternoon before the day power load has been cut off. This overlapping causes a very sharp peak in the load curve in many cases. In Fig. 125 typical average curves are shown for a lighting feeder which carries some day power load, for the months of March, June, September and December. The energy loss

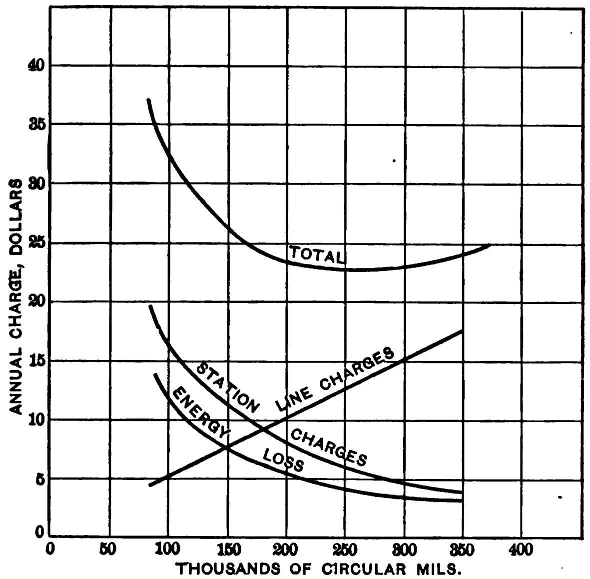



Fig. 126. Elements of Annual Cost of Maintaining a Circuit.

will evidently be different on this feeder each month in the year, being least during the summer months and most during December. Fig. 129 shows similar curves for a power circuit which carries some lighting during the evening. This curve is also similar to that which prevails on a transmission system where a considerable amount of power is supplied to industrial concerns during the day.

The annual loss on a circuit carrying load of given characteristics may be computed with sufficient accuracy for practical purposes as follows:

Taking the curve representing an average day in March, assume a resistance of one ohm and compute the value of $C^2R$ for each hour of the day. The sum of these 24 quantities is proportional to the kilowatt hours' loss on an average day in March. Repeat this operation for the June, September and December curves. Add the sum of the four curves and multiply by 91, this being the number of days in each quarter of the year. This grand total is proportional to the annual loss in kilowatt hours on any feeder carrying a load having the general characteristics assumed.

In cases where power is generated by water fall, the energy loss on the feeder may be neglected. The power absorbed by the line at the time of maximum load must be considered, however, in case it has a marketable value when the plant is fully loaded.

TABLE XI. — COST OF LEAD-SHEATHED CABLES.

| Size conductor. | Cost per 1000 c.m. per 1000 feet. | | | |
|---|---|---|---|---|
| | Single cond. 3000 volts. | Three cond. 10,000 volts. | Single cond. 300 volts. | Three cond. 300 volts. |
| 4 | $2.80 | $2.60 | $2.40 | $2.05 |
| 2 | 2.20 | 2.05 | 1.95 | 1.85 |
| 0 | 1.90 | 1.75 | 1.70 | 1.60 |
| 00 | 1.65 | 1.55 | 1.60 | 1.50 |
| 000 | 1.50 | 1.45 | 1.45 | 1.40 |
| 0000 | 1.40 | 1.35 | 1.35 | 1.30 |
| 250,000 | 1.30 | 1.25 | 1.30 | 1.25 |
| 350,000 | 1.20 | ............. | 1.15 | ............ |
| 500,000 | ............... | ............. | 1.00 | ............ |
| 750,000 | ............... | ............. | .90 | ............ |
| 1,000,000 | ............... | ............. | .80 | ............ |

**Loss Factor.** — The ratio of the loss as thus calculated to the value of the loss if the feeder had carried the maximum load of the year every hour of the year may be called the

*loss factor*, just as the ratio of the actual output for the year to the possible output at the rate of the maximum load is called the *load factor* of a circuit.

For instance, if a circuit carries a maximum load of 100 K.W. and delivers an amount of energy equivalent to a load of 100 K.W. during 2190 hours per year, the load factor of the feeder for the year is $\frac{2190}{24 \times 365} = 25$ per cent.

Similarly if the total kilowatt hour *loss* on a circuit for a year is equivalent to the loss at maximum load multiplied by 2190, the loss factor for the feeder year is 25 per cent.

If $C$ is the current at the annual maximum load and $R$ is the resistance per 1000 feet of conductor, the loss at the time of the annual maximum load is $C^2R$.

If the loss factor of the feeder is 20 per cent, the annual loss is

$$\frac{C^2R \times .2 \times 365 \times 24}{1000} = 1.752\, C^2R.$$

The loss factor for a load having the characteristics illustrated in Fig. 125 is 16 per cent, while that of the curves in Fig. 129 is 25 per cent.

In a constant-current circuit the loss factor is the ratio of the number of hours the circuit is operated during the year to the total number of hours in the year. It is usually the same as the load factor of the circuit.

**Calculation of Loss.** — When the character of the load curve is known, the loss factor may be determined in the manner described and the annual loss of energy calculated in terms of $R$, the resistance per 1000 feet of conductor, without difficulty.

The loss at the time of the annual maximum load being $C^2RL$, the annual loss in kilowatt hours is equivalent to the product of the maximum load loss by the number of hours in the year and by the loss factor.

There being 8760 hours in a year, this is $\frac{C^2RL \times 8760 \times F}{1000}$ $= 1.4\,C^2RL$ when the loss factor is 16 per cent. The value of this energy may be computed at the cost of fuel and supplies, as no extra labor is required to deliver it, as a rule. The cost can therefore be taken at about 1 cent in smaller plants, .70 cent in larger engine plants and .5 cent to .4 cent in turbine plants.

At 1 cent per kilowatt hour the value of the energy loss per conductor is $c = .014\,C^2RL$ dollars per year at 16 per cent loss factor or $.021\,C^2RL$ at 24 per cent loss factor.

**Summary of Annual Costs.** — The total annual cost is therefore the sum of the three quantities $a$, $b$ and $c$. For weatherproof wire with station capacity at $100 per kilowatt, a loss factor of 16 per cent and energy at 1 cent a kilowatt hour, the annual cost is

$$a + b + c = \frac{.513\,L}{R} + .012\,C^2RL + .014\,C^2RL$$

$$= \frac{.513\,L}{R} + .026\,C^2RL.$$

It is desired to ascertain when the value of these three elements will be a minimum for given values of $C$, the current at the time of the annual maximum load, and $L$, the length of conductor in thousands of feet. The only variable in the equation being $R$, the value of $a + b + c = y$ will be a minimum, according to the rule of the calculus, when $\frac{Dy}{dR} = 0$.

If $y = \frac{.513\,L}{R} + .026\,C^2RL$, then $\frac{Dy}{dR} = \frac{.026\,C^2R^2L - .513\,L}{R^2}$.

When this is 0, $.026\,C^2R^2L - .513\,L = 0$ and $C^2R^2 = \frac{.513}{.026}$ $= 19.7$, whence $CR = \sqrt{19.7} = 4.44$ and $R = \frac{4.44}{C}$ when the

most economical size is used. For instance, if $C = 100$ amperes, $R = .0444$ ohm, which is about the resistance per 1000 feet of 4/0 cable.

It is apparent from this result that the length of the circuit does not affect the economical size for a given value of maximum load current. The doubling of the length of a line doubles all the elements of cost, and therefore has no effect on the point of minimum annual cost, as long as the working voltage remains the same.

In distribution work, the voltage being fixed by practical considerations of safety to employees and continuity of service, as well as by the nature of the current whether direct or alternating, the current values and sizes of conductors are fixed by the load on the circuit. With transmission lines, the voltage is limited somewhat by the cost of insulating wires and apparatus, but the upper limit is usually fixed by the practicability and safety of operation. The voltage being chosen as high as is practicable, the maximum load current is thus fixed, and the best size of conductor for that load may then be determined by the foregoing method.

**Practical Illustrations.** — For illustration, a few cases which are common in practice for both larger and smaller systems are carried through herewith.

*Case I.* Value of weatherproof wire taken at 15 cents per pound with generating capacity at $125 per kilowatt, energy at 1 cent per kilowatt hour, and a load curve such that the loss factor is 12 per cent. Under these conditions $a = \frac{.513\,L}{R}$, $b = .015\,C^2RL$, $c = .0105\,C^2RL$, and the total cost is $\frac{.513\,L}{R} + .0255\,C^2RL$. Whence $C^2R^2 = \frac{.513}{.0255} = 20.1$ and $CR = 4.48$ for each conductor carrying the current $C$.

This applies only to a two-wire or three-wire circuit in which each conductor carries current normally. With a three-wire Edison feeder with neutral half the size of the outers the amount of copper is increased 25 per cent, without increasing $b$ and $c$, and $a = \frac{.513 \times 1.25 L}{R} = \frac{.641 L}{R}$. Hence $CR = \sqrt{\frac{.641}{.255}}$ $= 5.01$ for the outer conductors of a three-wire circuit.

Similarly with a four-wire three-phase feeder with neutral the same size as the phase wires the amount of copper is increased 33 per cent and $a = \frac{.513 \times 1.33 L}{R} = \frac{.684}{R}$, whence $CR = \sqrt{\frac{.684}{.0255}} = 5.17$.

These values involve a current density of about .5 ampere per 1000 circular mils, which is much lower than is commonly found. This is due in part to the fact that the expenditure of funds for line conductors is plainly before the engineer, while the value of the generating capacity which he ties up by cutting the size of the conductor to a minimum is not so apparent. Often, too, there is reserve generating capacity, which is already paid for and can as well be used to supply line losses as not. Under circumstances where generating capacity can be ignored, the annual cost becomes $a + c$, which for the conditions assumed for a two-wire feeder is

$$\frac{.513 L}{R} + .0105\, C^2 RL.$$

Hence $CR = \sqrt{\frac{.513}{.0105}} = 7.0$ for a circuit in which each wire carries current,

or $CR = \sqrt{\frac{.641}{.0105}} = 7.81$ for a 3-wire Edison feeder with neutral half size,

or $CR = \sqrt{\frac{.684}{.0105}} = 8.07$ for a 4-wire 3-phase feeder neutral same size.

*Case II.* Weatherproof wire at 15 cents a pound, generating capacity at \$80 a kilowatt, energy .5 cent per kilowatt hour, and load curve such that the loss factor is 18 per cent. Under these conditions

$$a = \frac{38 \times .15 \times .09\,L}{R} = \frac{.513\,L}{R}, \quad b = \frac{80 \times .12}{1000}\,C^2RL = .0096\,C^2R,$$

$$c = \frac{.005 \times 8760 \times .18\,C^2RL}{1000} = .0079\,C^2RL.$$

Hence $CR = \sqrt{\frac{.513}{.0175}} = 5.43$ per conductor which carries a current $C$.

If generating capacity is ignored, $CR = \sqrt{\frac{.513}{.0079}} = 8.1$. This calls for a conductor having .081 ohm resistance for 100 amperes, which is about equivalent to 1260 circular mils per ampere. For three-wire Edison circuits $CR = 9.0$ and for four-wire three-phase circuits $CR = 9.3$.

*Case III.* Underground cables at values given in Table XI, generating capacity at \$80 per kilowatt, energy at .4 cent per kilowatt hour, and loss factor at 25 per cent. With single-conductor low-tension cable, No. 2 to 2/0, the cost per 1000 c.m. averages \$1.80.

Hence $$a = \frac{.09 \times 10.4 \times 1.8\,L}{R} = \frac{1.68\,L}{R},$$

$$b = \frac{80 \times .12\,C^2RL}{1000} = .0096\,C^2RL,$$

$$c = \frac{.004 \times 8760 \times .25\,C^2RL}{1000} = .0087\,C^2RL,$$

and $CR = \sqrt{\frac{1.68}{.0183}} = 9.5$ per conductor carrying current $C$.

With 100 amperes $R = \frac{9.5}{100} = .095$, which is nearly the

resistance of No. 0 conductor. Hence the value of cable assumed was practically correct.

If the current were 500 amperes, the value of cable would be chosen for about 750,000 c.m., which is \$.90. Then

$$a = \frac{1.68 \times .90}{1.8\,R} = \frac{.84}{R}, \qquad CR = \sqrt{\frac{.84}{.0183}} = 6.7.$$

At 500 amperes $R$ should be made $\frac{6.7}{500} = .0134$, which is approximately the resistance of a 750,000 c.m. cable. Neglecting generating capacity, $CR = 13.8$ at 100 amperes.

If this were a low-tension feeder with neutral half size the cost of the feeder would be \$1.80+\$1.30 = \$3.10 per 1000 c.m. Hence

$$a = \frac{3.10 \times .09 \times 10.4\,L}{R} = \frac{3.00}{R}, \quad b = 2 \times .0096\,C^2RL = .0192\,C^2RL$$

and $c = 2 \times .0087\,C^2RL = .0174\,C^2RL$ for the feeder.

$$CR = \sqrt{\frac{3.00}{.0366}} = 9.0 \text{ and } R = \frac{9.0}{500} = .018,$$

which is between the resistance of 500,000 and 600,000 c.m. cable. This is for the outer wires only, the neutral being considered as carrying no load and as half the size of the outer.

In the case of a four-wire three-phase feeder with neutral the same size as the phases, the value of the feeder at 100 amperes is $4 \times 1.90 = \$7.60$ and $a = \frac{7.11\,L}{R}$.

$$b + c = 3 \times .0183\,C^2RL = .0549\,C^2RL.$$

Hence $\qquad CR = \sqrt{\frac{7.11}{.0549}} = 11, \quad R = \frac{.11}{100} = .011,$

which is nearest the resistance of No. 0 cable.

Neglecting generating capacity $CR = 16$ at 100 amperes for a four-wire three-phase circuit.

*Case IV.* Three-conductor cables, generating capacity at \$80 per kilowatt, energy at .4 cent per kilowatt hour and loss factor at 25 per cent, 2000 volts three phase, 100 amperes. The cost of cable is \$1.50 per thousand circular mils.

$$a = \frac{\$1.50 \times .09 \times 10.4 L}{R} = \frac{1.41}{R} \text{ per conductor.}$$

$b + c = .0183\, C^2RL$ per conductor, as each carries the current $C$.

$CR = \dfrac{1.41}{.0183} = 8.8,\quad R = \dfrac{8.8}{100} = .088$, which is nearest the resistance of 2/0 cable.

*Case V.* Bare wire overhead, water power generating capacity at \$100 per kilowatt, copper at 15 cents per pound, current 150 amperes. The depreciation item in the fixed charges on conductors may be ignored, as there is no insulation to be replaced. Fixed charges may therefore be computed at 5 per cent interest and 1 per cent taxes, or 6 per cent on the line wire.

$W = \dfrac{32}{R}$ and the cost per 1000 feet is $.15\, W = \dfrac{.15 \times 32}{R}$.

Hence $$a = \frac{.06 \times .15 \times 32 L}{R} = \frac{.288 L}{R}.$$

The value of station capacity at \$100 per kilowatt is $\dfrac{100\, C^2RL}{1000} = .1\, C^2RL$ and $b = .1 \times .12\, C^2RL = .012\, C^2RL$. The power being derived from water $c = 0$. The annual cost is

$a + b = \dfrac{.288 L}{R} + .012\, C^2RL. \quad CR = \sqrt{\dfrac{.288}{.012}} = 4.9.$

At 150 amperes $R = \dfrac{4.9}{150} = .032$, which is about the resistance of a 300,000 c.m. cable.

This represents a very low current density, due to the fact that fixed charges on line capacity are less than half those on

station capacity. It is therefore economical to invest money in line conductors which will make more of the generating capacity available for commercial load.

*Case VI.* Constant-current system, direct current, 7 amperes, weatherproof wire, generating capacity $200 per kilowatt, cost of energy 1 cent per kilowatt hour, operated dusk to daylight every day, making the loss factor 50 per cent.

As in Case I, $a = \frac{.513L}{R}$ for weatherproof wire. The cost of generating machinery for this class of service is usually very high. Where direct current is used the units must be small and the cost per kilowatt high, as the generators themselves cost more on account of the high voltage and the arrangement for driving, whether by motors or shafting, is necessarily expensive. Where the shafting is dispensed with and the generators are driven by alternating-current motors, the investment per kilowatt is very high, as the capacity of alternating-current generator, alternating motor and constant-current generator must be included in figuring the cost per kilowatt of capacity. At $200 per kilowatt,

$$b = \frac{200 \times .12}{1000} C^2RL = .024\, C^2RL.$$

With energy at 1 cent per kilowatt hour and the loss factor at 50 per cent $c = \frac{.01 \times 8760 \times .5}{1000} C^2RL = .043\ C^2RL.$

The total is therefore $\frac{.513L}{R} + .067\ C^2RL$, whence $CR = \sqrt{\frac{.513}{.067}} = 2.8$. At 7 amperes $R = .4$ ohm, which is nearly the resistance of No. 6 B. & S.

In cases where distributing feeders are supplied through a transformer substation, the calculation for the best size of feeders should be made with the cost of generating, trans-

mission and substation equipment in view, in determining the fixed charges on generating capacity.

The curves in Fig. 126 show how the line charges, station capacity charges and line losses (with steam power) are related to each other where the line current is 100 amperes. The line is weatherproof wire, and other conditions are those assumed in Case I.

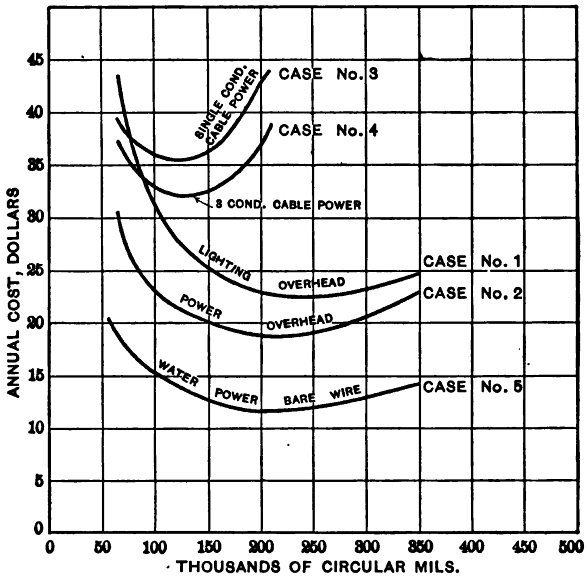


Fig. 127. Annual Cost Under Various Conditions.

The application of the foregoing principles to distributing mains cannot be carried out, as such mains carry indeterminate loads and should be so designed that the drop on them will not exceed 2 per cent. In many cases this requirement involves the use of larger conductors than would be required from mere economic considerations of line loss. In other words the economic limit in this part of the system is the life and performance of incandescent lamps, and these often far outweigh line losses in mains.

In large distributing systems it is customary to establish certain standard loads for feeders, beyond which it is considered undesirable to go. The maximum ampere load being thus established, the size of conductors is readily determined by one of the foregoing methods.

In alternating-current systems the selection of transformers and their location with reference to the secondary mains involves economic considerations which are very complex and do not admit as simple a solution as is possible with feeders and transmission lines. This subject is fully discussed in the chapter on Secondary Distribution.

**Diversity Factor.** — In the distribution of electricity in a large city for general lighting and power purposes, the maximum demands of consumers are made at different hours of the day, and vary from day to day during the week and from month to month during the year. The maximum demands of lighting consumers are affected by the changing seasons, by the character of the population served, and by the nature of the premises in which the lighting is used.

Some manufacturers use more power before noon, while others, such as foundries, use more in the afternoon.

The demand for electricity for power purposes is greatest during the hours when the lighting load is smallest. The combined effect of these influences is to produce a smaller maximum demand at the point of supply than would be required if these demands were coincident. The sum of the maximum demands of individual consumers is greater than that on the distributing mains from which they are supplied. The sum of the maxima on distributing mains is greater than that on the feeder, the sum of the feeder maxima is greater than that at the substations, and the sum of the substation maxima is more than the coincident maximum of the generating station.

The ratio of the sum of the maxima of the subdivisions of any part of the distributing systems to the coincident maximum demand observed at the point of supply is called the *Diversity Factor* of that part of the system. Thus if the sum of the maxima on a group of consumers' meters were 200 K.W. and the coincident maximum at the transformer serving them were 100 K.W., the Diversity Factor would be $\frac{200}{100}$, or 2.

The diversity factor is different between the individual users of a group of residence consumers from what it is for those of a group of stores or factories.

The residence consumer varies his demands according to the size and character of his dwelling place, having his house well lighted at times and almost totally dark on other evenings. Perhaps his neighbors are well lighted up on the evenings when he is not at home. Thus the maximum demands of individual consumers come on different days or at different hours of the day, so that their sum is much greater than the highest demand made upon the distributing system at one time.

With store and other commercial lighting, the demands of the individual users are apt to be more uniform, since the conditions under which lighting must be used are fixed by practical necessity and by customs which the user is not at liberty to ignore. The proprietor of the store must burn his window lights in order to compete with his neighbors, and the owner of the factory must furnish his employees sufficient light to enable them to work to advantage. The diversity factor between such consumers is therefore smaller than it is between residence consumers.

The study of diversity factors for various classes of consumers is a matter of great importance to the financial success of a central station business and is so intimately involved with the design of the distributing system that the engineer should

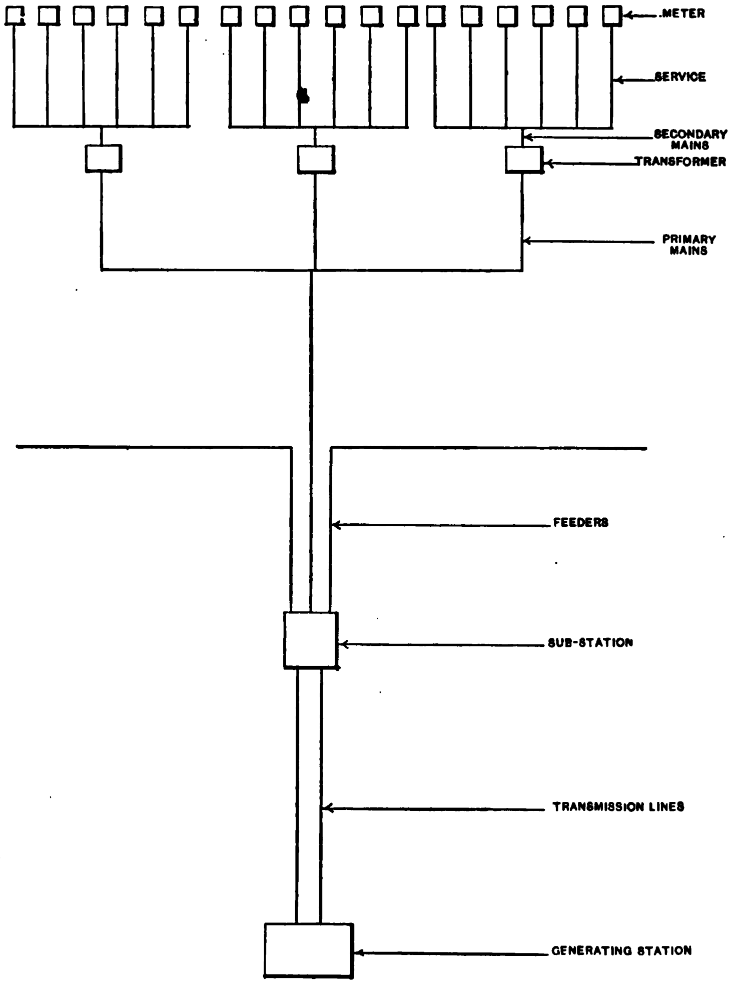



Fig. 128. Elements of a Distribution System.

be fully informed as to the effect of diversity factors upon the generating and distributing systems.

An analysis of diversity factors for various classes of consumers in the city of Chicago has been made by the authors, based upon observations made at various points in the alternating-current distributing system.

The observations were taken at the consumers' meters, at the line transformers, at the substation switchboard and at the generating station. The relation of these various points is illustrated diagrammatically in Fig. 128.

Consumers of electricity may be classified as residence light, commercial light, general power and large users. The commercial light includes the average small and medium-sized stores and shops whose maximum demand is under 50 K.W.; general power includes all miscellaneous power users having less than 50 K.W.; while large users are the light and power consumers having 100 to 500 K.W.

**Diversity Factors for Various Classes of Consumers.** — The observations made and results calculated for the various classes of consumers are presented in Table XII. Group A is a residence block supplied by one transformer, in which there are 34 consumers having a connected load of 18 K.W. or an average of .53 K.W. per consumer. The sum of the consumers' maxima is 12 K.W., while the actual maximum as measured on the transformer is 3.6 K.W. The ratio of the consumers' maxima to the transformer maximum is 3.33, which is the diversity factor between the consumers in this block. The average load factor of this group of consumers is 7 per cent, considered individually, while the load factor of the energy delivered from the transformer is 23.1 per cent.

Group B is a similar block having 185 consumers with the same average connected load. The sum of the consumers'

maxima is 68 K.W., the transformer maximum is 20 K.W., the diversity factor is 3.4, and the transformer load factor is 23.8.

The premises lighted by these two transformers were practically all apartments and the public halls of the same.

TABLE XII.

RESIDENCE LIGHTING.

| Group. | No. of cons. | K.W. conn. per cons. | Sum of cons. max. | Max. of group. | Diversity factor. | Aver. cons. load factor. | Group load factor. |
|---|---|---|---|---|---|---|---|
| A | 34 | .53 | 12 | 3.6 | 3.33 | 7. | 23.1 |
| B | 185 | .53 | 68 | 20. | 3.40 | 7. | 23.8 |
| C | 167 | .87 | 93 | 28. | 3.32 | 7.3 | 24.0 |
| Aver. | 128 | .68 | 57 | 17.2 | 3.35 | 7.1 | 23.9 |
| | | | COMMERCIAL LIGHTING. | | | | |
| D | 46 | 1.28 | 46 | 33 | 1.40 | 13 | 18 |
| E | 79 | .74 | 36 | 26 | 1.40 | 11 | 16 |
| F | 160 | .53 | 62 | 41 | 1.51 | 10 | 15 |
| Aver. | 95 | .70 | 48 | 33 | 1.46 | 10.8 | 15.7 |
| G | 221 | 2.70 | 403 | 270 | 1.48 | 13 | 19 |
| | | | GENERAL POWER. | | | | |
| | | H.P. | K.V.A. | K.V.A. | | | |
| H | 29 | 1.3 | 30 | 21 | 1.43 | 15 | 21 |
| I | 18 | 3.3 | 40 | 25 | 1.60 | 16 | 26 |
| J | 11 | 11.8 | 90 | 65 | 1.39 | 18 | 28 |
| K | 25 | 6.0 | 100 | 70 | 1.43 | 21 | 30 |
| Aver. | 21 | 4.5 | 65 | 45 | 1.44 | 17.5 | 26 |

In Group C the premises were about two-thirds small apartments and the remainder large apartments and residences. This accounts for the greater connected load and the larger average load on this transformer. The diversity factor, however, remains practically the same as in the previous cases.

The determination of the sum of consumers' maxima in cases where the connected load is less than 1 K.W. is based

upon averages worked out from the readings of demand meters. The schedule of individual consumers' demands used in these calculations was as follows:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Connected load 50-watt equivalent.. | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 19 |
| Maximum 50-watt equivalent....... | 3 | 5 | 6 | 6.5 | 7 | 8 | 8 | 9 | 10 |

These maxima were determined from the averages of the demand meter readings of over 20,000 residence consumers, and may be safely applied to groups of consumers as large as those under consideration.

The transformer maxima were taken during the winter months between 7 and 8 P.M., this being the hour when the maximum load occurs in the districts in which observations were taken.

Of the three groups of commercial light consumers, it will be noted that group D consists of 46 consumers having an average connected load of 1.28 K.W. The total of the consumers' maxima is 46 K.W., the transformer maximum is 33 K.W. and the diversity factor is 1.4. This group consists of small stores on an outlying business street, with several saloons and restaurants.

In group E there are 79 consumers having an average connected load of .74 K.W. and a diversity factor of 1.4. There are no large stores in this group and no saloons or restaurants.

In Group F there are 160 consumers with an average connected load of .53 K.W. and a diversity factor of 1.5. This group includes eight or ten apartments above stores and an equal number of offices, lodge halls, etc., which tend to increase the diversity factor and to lower the average consumer's load factor.

Group G is an 18-story office building in which there are 221 consumers including the lighting and general power service of the building owner. The connected load of 603 K.W. includes 180 horse power in ventilating fans, pumps and such

other machinery as is used in an office building having hydraulic elevators. The average load per consumer is 2.7 K.W., the sum of the consumers' maxima is 403 K.W., the maximum as measured on the feeder at the substation switchboard is 270 K.W. and the diversity factor is 1.48. The consumers' maxima were determined from demand meter readings for the most part in this case. This is not strictly commercial lighting, as the power load could not be measured separately and is included in the maximum of 256 K.W. for the building.

Among the general power users, group H consists of 29 single-phase consumers having a connected load of 37 horse power and an average load of 1.3 horse power. The sum of the consumers' maxima is 30 K.V.A., the transformer maximum is 21 K.V.A. and the diversity factor is 1.43. These consumers are sweat shops manufacturing men's clothing.

Group I consists of 18 consumers having 60 horse power in single-phase and three-phase motors whose average horse power connected is 3.3. The diversity factor for this group is 1.6. Ten of these are single-phase consumers manufacturing clothing and the other eight are three-phase consumers using power for various other manufacturing processes.

Group J consists of eleven consumers having an average load of 11.8 horse power whose diversity factor is 1.39. The largest consumer in this group has wood-working machinery which is operated steadily and accounts for the higher transformer maximum and lower diversity factor.

In Group K, 25 consumers have an average installation of 6 horse power with a diversity factor of 1.43. About fifteen of this group are small clothing manufacturers having less than 5 horse power.

The consumers' maxima for these groups were determined on the basis of maximum demands of several thousand similar direct-current consumers who were equipped with demand

meters. The transformer maxima were measured between 10 and 11 A.M., this being the hour when the alternating power current load is a maximum in Chicago.

The consumers' load factors which appear in this table for power users were taken from a paper read by Mr. E. W. Lloyd before the National Electric Light Association at its 1909

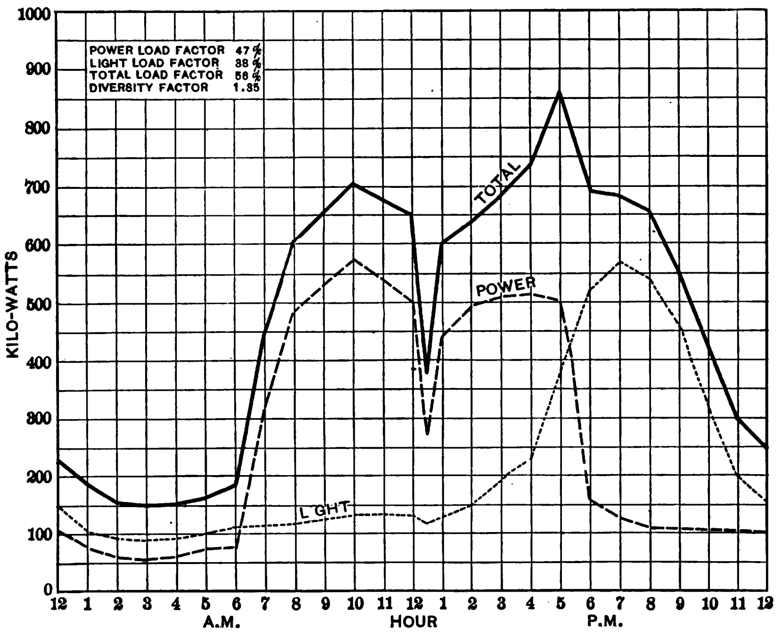



Fig. 129. Diversity Between Light and Power Loads.

convention. His results were derived from a large number of demand and wattmeter meter readings on various classes of power users.

With large users the larger part of the diversity arises between different parts of the premises. In a large mercantile store there are always some departments where business is dull at a time when it is good in another department and *vice*

*versa*. Likewise in a large manufacturing establishment the requirements of different departments for power vary with different hours of the day and different days of the week. The maximum demands of large users therefore vary by a smaller percentage from day to day than those of small consumers, and the principal source of diversity between large users

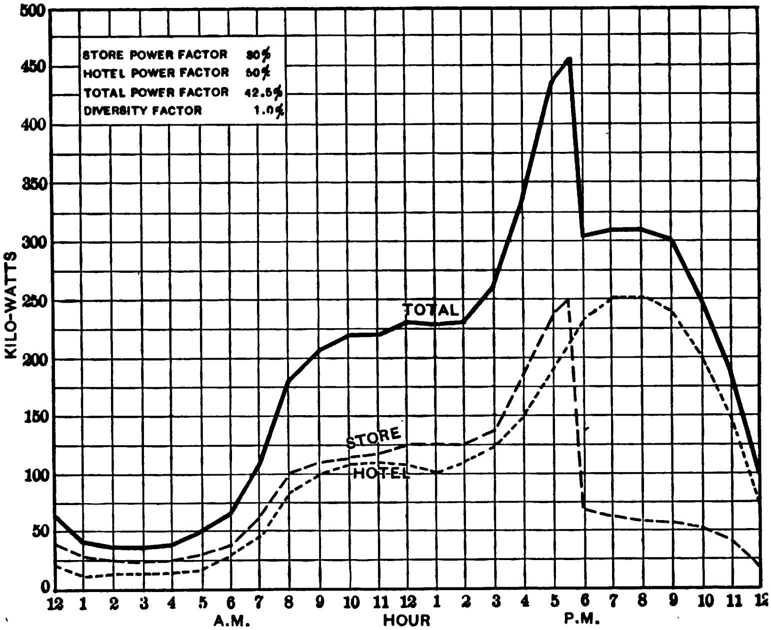



Fig. 130. Load Diagrams, Day and Evening Users.

arises from differences in the general character of their requirements.

The curves in Fig. 129 show the result of combining the demands of a large day power user and a large evening light user. The sum of the demands of these consumers is 1150 K.W., while the coincident maximum demand, which occurs at 5 P.M., is but 850 K.W. The diversity factor between these two consumers is therefore 1.35.

The diversity factor between a large mercantile establishment located in the central business portion of the city and a large evening light user, such as a hotel, is shown in the load diagram in Fig. 130, the diversity factor being 1.09.

**Diversity between Transformers.** — The diversity between different transformers on the same feeder is similar to that between large users. A study of the amount and character of load on the various transformers in conjunction with representative tests of transformer loads makes it possible to derive diversity factors for feeders which are reasonably accurate.

Analyses made of feeders supplying residence territory with about 25 per cent of small store lighting and less than 5 per cent of power load, indicate an average diversity factor of 1.2. Feeders supplying about equal amounts of residence and commercial lighting with 25 per cent of power show diversity factors of about 1.3. Feeders supplying a large number of scattered power consumers with 40 per cent to 50 per cent of lighting have diversity factors of 1.8 to 2.

**Diversity between Feeders.** — At the substation bus bar there is a further diversity between feeders. In a certain substation having a load of 3500 K.W. which is 90 per cent lighting, the maximum load on most of the feeders occurs at 7.30 P.M. in December, the other feeders having their maxima at 5 P.M. The diversity factor of the feeders in this station during the week of the maximum load of the year was 1.05.

In a 2700-K.W. substation the maximum load on 90 per cent of the feeders occurs at 5 P.M., due to a large proportion of store and factory light and power, and the diversity factor between feeders was 1.06 during the week of the maximum load of the year.

In two other substations of nearly the same size about 60 per cent of the feeders have 7.30 P.M. maxima and 40 per cent have 5 P.M. maxima. In these substations the diversity factor was 1.14 and 1.15 respectively during the week of the annual maximum.

In another case where about half of the feeder maxima occur at 5 and half at 7.30 P.M. the feeder diversity factor was 1.36.

**Diversity between Substations.** — At the generating station there is a diversity factor between the substations having 5 P.M. maxima and those having maxima at other hours. This depends largely upon the number of substations of each kind and their loads. Where there is about 25 per cent of the light and power load of the city which has a 7.30 P.M. maximum, as is the case in Chicago, the diversity factor between substations is about 1.1.

**Total Diversity.** — The total diversity factor of the generating and distributing system is the continued product of the diversity factors between consumers, transformers, feeders and substations. In the case of residence consumers, the total diversity factor is the product of $3.35 \times 1.3 \times 1.15 \times 1.1$. This amounts to 5.52. For commercial lighting consumers the total diversity factor is 2.41. For general power consumers the total diversity factor is 2.26 and for large users 1.45. These are the diversity factors from the consumer's meter to the generating station.

The average diversity factors for the four classes of consumers and the total diversity factor from the consumer to the generator are presented in Table XIII.

The total diversity factor of a distributing system is obtained by combining those of the various classes of consumers. In the Chicago system the diversity factor of the general

lighting and power load, not including electric railways, is 3.2 during the winter months.

TABLE XIII. — DIVERSITY FACTORS.

| | Residence light. | Commercial light. | General power. | Large users. |
|---|---|---|---|---|
| Between consumers | 3.35 | 1.46 | 1.44 | ......... |
| " transformers | 1.3 | 1.3 | 1.35 | 1.15 |
| " feeders | 1.15 | 1.15 | 1.15 | 1.15 |
| " substations | 1.1 | 1.1 | 1.1 | 1.1 |
| Consumer to transformer | 3.35 | 1.46 | 1.44 | ......... |
| " " feeder | 4.36 | 1.90 | 1.95 | 1.15 |
| " " substation | 5.02 | 2.19 | 2.24 | 1.32 |
| " " generator | 5.52 | 2.41 | 2.46 | 1.45 |

The effect of the diversity factor upon the load factor is to increase it almost in direct proportion to the diversity factor. The load factor of residence consumers individually is but 7 per cent, while in groups it is about 23 per cent, and similarly the collective load factor of a group of commercial lighting consumers is about 16 per cent and for general power users it is about 17 per cent.

When these classes of consumers are combined at the generating station their load factor is about 35 per cent during the winter months in the Chicago system.

**Economic Significance.** — The economic significance of the diversity factor lies in the effect produced upon the investment required to carry on the business.

For instance, in the case of residence lighting, for each 100 K.W. of consumers' demand there is required $\frac{100}{3.35} = 30$ K.W. of transformer capacity and $\frac{100}{5.02} = 20$ K.W. (approx.) of substation capacity or $\frac{100}{5.52} = 18.1$ K.W. of generating capacity.

Similarly for commercial lighting or small power the generating capacity is 41.0 K.W. per 100 K.W. of consumers'

demand, while for large users about 70 K.W. capacity is required.

These generating capacities are based upon an assumption of 100 per cent efficiency in the converting and distributing system. In practice the system efficiency is about 75 per cent at the time of the maximum load of the year, and it is therefore necessary to add about one-third to the above figures before making comparisons with any particular generating system.

In the Chicago system as operated in 1909 there were required 42 K.W. of generating capacity for each 100 K.W. of individual consumer's demand, losses being included.

The cost of production of electricity is made up of fixed charges and operating expenses. The fixed charges constitute about one-half the total cost. The fixed charges being determined by the amount of the investment, it is very important to understand the effect of the diversity factor on the investment.

Likewise operating expenses tend to diminish as the load factor increases, and the effect of the diversity factor upon load factor should be well understood.

## CHAPTER XIII.

### PROPERTIES OF CONDUCTORS.

THE fundamental unit in electrical distribution is the conductor. A thorough knowledge of the physical properties of the conductors of electricity is therefore indispensable to the distribution engineer.

While all metals are conductors of electricity, each has its own characteristics of resistance, temperature, coefficient and mechanical strength.

Copper being among the best conductors and sufficiently plentiful in nature, is the metal most commonly employed for distribution work. Aluminum is used in transmission work to some extent, because of its low specific gravity. Iron is used as an electrical conductor in railway work, where the rails carry the return current to the power house, and in third-rail systems the supply to the motor cars is so carried.

German silver and other alloys are used in making resistance coils for rheostats carrying small currents. Silver is a better conductor than copper, but its value is too great to permit its use for electrical work, except for special purposes where no considerable quantity is required.

**Resistance and Conductivity.** — The resistances of metals are compared by reducing them to a common standard called the specific resistance. A wire of any metal one foot long and .001 inch in diameter has a certain resistance at 32 degrees F. which is called the specific resistance of that metal. It may be expressed in ohms per mil foot or in microhms per cubic centimeter. The ohms per mil-foot basis is the most

convenient for practical use, since conductor areas are measured by circular mils.

The reciprocal of resistance is known as conductivity. The specific resistance of copper, for instance, is 9.59 ohms per mil foot at 32 degrees F. Its conductivity is therefore $\frac{1}{9.59} = .1042$.

For comparative purposes it is customary to express the conductivity of other metals in terms of a percentage of the conductivity of copper. In the first column of Table XIV,

TABLE XIV. — CONDUCTIVITIES OF VARIOUS METALS.

| | Per cent conductivity. | Per cent resistance. | Ohms per mil ft. at 0 deg. C. | Temp. coefficient, per deg. C. | Temp. coefficient, per deg. F. |
|---|---|---|---|---|---|
| Silver | 108.2 | 92.5 | 8.83 | .00400 | .00222 |
| Commercial copper | 100 | 100 | 9.59 | .00426 | .00236 |
| Gold | 72.5 | 138 | 13.22 | .00377 | .00210 |
| Aluminum | 62.1 | 161 | 15.37 | .00423 | .00235 |
| Zinc | 27.6 | 362 | 34.55 | .00406 | .00225 |
| Platinum annealed | 17.7 | 565 | 53.96 | .00247 | .00137 |
| Iron | 17.6 | 570 | 54.51 | .00625 | .00347 |
| Nickel | 12.9 | 778 | 75.30 | .0062 | .00345 |
| Tin | 12.1 | 828 | 78.70 | .0044 | .00245 |
| Lead | 7.82 | 1280 | 120.60 | .0041 | .00228 |

for instance, the conductivity of aluminum is 62 per cent. This means that if an aluminum wire is loaded with 62 per cent as much current as a copper wire of equal size and length, the energy loss is the same in each. Or if they carry the same current, the aluminum wire must be $\frac{100}{62} = 1.6$ times as large in cross-section as the copper conductor for equal loss of energy.

**Temperature Coefficients.** — The resistance of a metallic conductor increases or decreases with a rise or fall of temperature in the conductor. The change in resistance is pro-

portional to a constant which is determined experimentally and which is different for the various metals.

In annealed copper the resistance of a conductor at a given temperature $t$ is $R = R'(1 + .00426\,t)$ when $t$ is expressed in degrees Centigrade, or $R = R'(1 + .00236\,(t - 32))$ when $t$ is expressed in degrees Fahrenheit. $R'$ is the resistance of the conductor at 0 degrees C. or 32 degrees F. The resistance at 32 degrees F. is not usually known and must therefore be determined from a known value of resistance which has been observed at some other temperature. For example if the resistance at 70 degrees has been observed, the resistance at 32 degrees may be calculated by reversing the above equation, after which the resistance at any other temperature above or below 70 degrees may be readily calculated. For instance, if the resistance of a conductor were observed to be 10 ohms at 70 degrees F., what would it be at 100 degrees F.?

$$R = 10 \text{ and } t - 32 = 38.$$

Hence $10 = R'(1 + .00236 \times 38)$

and $$R' = \frac{10}{1 + .00236 \times 38} = 9.18 \text{ ohms at 32 degrees F.}$$

At 100 degrees F., $t - 32 = 68$ and the value of the resistance becomes $R = 9.18\,(1 + .00236 \times 68) = 10.65$ ohms. That is, the resistance of the conductor has been increased 6.5 per cent by raising its temperature from 70 to 100 degrees.

The average temperature of a conductor may be calculated from measured values of resistance by means of the same formula, in the following manner.

The resistance is measured first at the temperature of the surrounding air, that temperature being noted and being assumed to be the same as that of the conductor. After having carried current until its temperature is increased, its resistance is again measured.

Assuming a conductor which is found to have a resistance of 10 ohms at 70 degrees F., what will be its average temperature when its resistance is 11.5 ohms? In the formula $R = 11.5$, $R' = 9.18$ and the equation is to be solved for the value of $t$.

$$11.5 = 9.18\,(1 + .00236\,(t - 32)) = 8.48 + .0217\,t,$$

whence $$t = 139 \text{ degrees F.}$$

The solution of such problems may be greatly facilitated by the use of a diagram such as that shown in Fig. 131. In this diagram the line designated copper shows the percentage of increase in the resistance of a copper conductor as its temperature varies from 30 degrees below 0 to 160 degrees F. above. The curve for iron is also included in the diagram, and curves for other metals may be added by computing two points at temperatures 40 or 50 degrees apart and drawing a straight line through them.

If a copper conductor has a resistance of 10 ohms at 70 degrees F., what will its resistance be at 100 degrees F.? Referring to the diagram it is seen that the resistance of any copper conductor increases 9 per cent in passing from 32 degrees to 70 degrees F., or 16.1 per cent to 100 degrees F. In passing from 70 degrees to 100 degrees F. it will therefore increase $\dfrac{16.1 - 9}{1.09} = 6.5$ per cent and its resistance will be $10 \times 1.065 = 10.65$ ohms. This is the result as found by the use of the formula above.

Again, if a conductor has a measured resistance of 10 ohms at 70 degrees F., what will be its average temperature when its resistance is 11.5 ohms?

The increase in resistance above 70 per cent is 15 per cent, hence the increase from 32 degrees F. to 70 degrees F. being 9 per cent, the increase from 32 degrees to $t$ is $1.09 \times 1.15 = 1.253$, or 25.3 per cent. Following the curve to the point

where it reaches 25.3 per cent, it is found that the temperature will be about 140 degrees F. This corresponds closely to the result of 139 degrees as calculated from the formula.

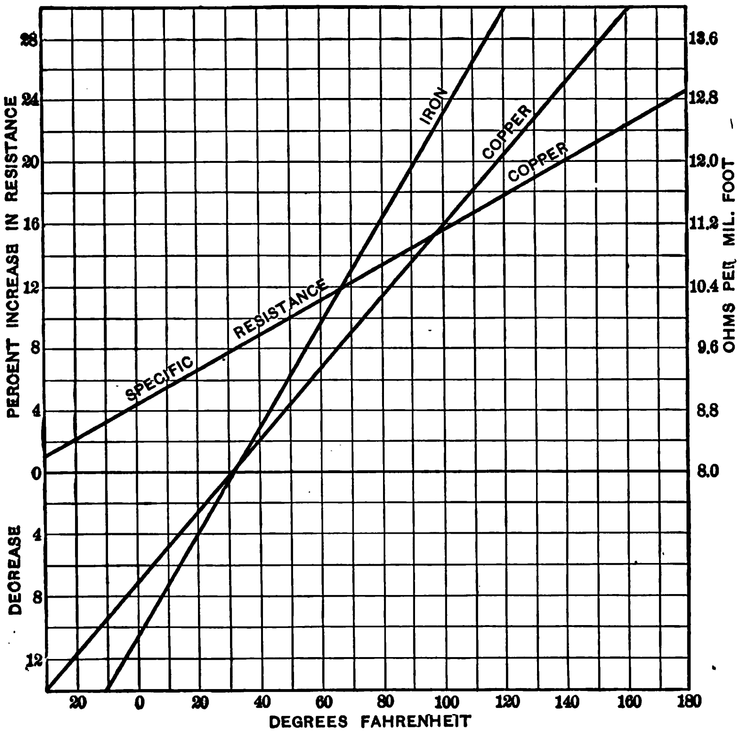



Fig. 131. Relation of Resistance and Temperature.

If more accurate results are required in the solution of such problems by the diagram, it may be drawn to a large scale with ample subdivisions in the temperature scale.

The temperature coefficients of copper and aluminum are fortunately about equal, and the diagram may therefore be used for aluminum conductors.

The temperature coefficients of various metals are embodied in Table XIV in terms of both Centigrade and Fahrenheit thermometer scales, together with values of specific resistance expressed in ohms per mil foot at zero Centigrade.

The value of the resistance of copper per mil foot changes with the temperature, and it is often convenient to know its value at various temperatures, since it is embodied in the formula for calculating voltage drop in conductors.

The line designated *Specific Resistance* in Fig. 131 shows these values for all ordinary temperatures up to 180 degrees F. For instance, the resistance of a mil foot of copper wire at 120 degrees F., as shown by the diagram, is 11.6 ohms, or at 70 degrees it is 10.5 ohms.

**Area of Cross-section.** — The area of cross-section of wires is commonly measured in circular mils, a circular mil being the area of a wire having a diameter of .001 inch. A circular mil therefore has an area of $.785 \times (.001)^2 = M$. A wire having a diameter of 325 mils or .325 inch, has an area of $.785 \times (.325)^2 = M \times (325)^2$. The area of a wire having a diameter of .325 inch is therefore 105,500 circular mils, which is the area of No. 0 wire B. & S. gauge.

The cross-section of a wire in circular mils is therefore the square of its diameter expressed in mils. The area of a conductor 1 inch or 1000 mils in diameter is therefore 1,000,000 circular mils.

Likewise, in reckoning the area of rectangular conductors, the area in square mils is the product of the width by the thickness expressed in mils. A square mil is $\frac{1}{.7854} = 1.274$ times a circular mil, and a circular mil is .7854 of a square mil. It is customary to express areas in square millimeters where the metric system is employed.

**Wire Gauges.** — The sizes of wires are expressed commercially by a series of numbers known as the wire-gauge table. In the early days of wire manufacture, each maker had his own gauge, and several standards became current. The Brown and Sharpe gauge is commonly used for copper conductors up to 460 mils or 211,600 circular mils, while the Edison circular mil gauge is used in larger sizes. The Washburn & Moen, and the Birmingham gauges, are used chiefly in connection with iron and steel wire cables and are rarely referred to in connection with electrical conductors.

The diameter of wires of sizes down to No. 12 in the Roebling, Washburn & Moen, Birmingham and Brown & Sharpe gauges are given in Table No. XV.

TABLE XV. — COMPARISON OF WIRE GAUGES.

| No. | Roebling, W. & Moen. | Brown & Sharpe. | Stubs Birmingham. |
|---|---|---|---|
| 6–0 | .460 | ............ | ............ |
| 5–0 | .430 | ............ | ............ |
| 4–0 | .393 | .460 | .454 |
| 3–0 | .362 | .4096 | .425 |
| 2–0 | .331 | .3648 | 380 |
| 0 | .307 | .3249 | .340 |
| 1 | .283 | .2893 | .300 |
| 2 | .263 | .2576 | .284 |
| 3 | .244 | .2294 | .259 |
| 4 | .225 | .2043 | .238 |
| 5 | .207 | .1819 | .220 |
| 6 | .192 | .1620 | .203 |
| 7 | .177 | .1443 | .180 |
| 8 | .162 | .1285 | .165 |
| 9 | .148 | .1144 | .148 |
| 10 | .135 | .1019 | .134 |
| 11 | .120 | .0907 | .120 |
| 12 | .105 | .0808 | .109 |

The Brown and Sharpe gauge, commonly referred to as B. & S., is based upon a geometric series, in which if "n" is the gauge number the diameter of the wire in inches is $d = \frac{.3249}{1.123^n}$. This works out so that every third number is

twice as heavy as the third higher number, and every tenth number is one-tenth of the weight of the tenth higher. That is, No. 10 is twice as heavy as No. 13, and half as heavy as No. 7. This is a very convenient fact to bear in mind, as by memorizing the diameter, resistance and weight of one size, such as No. 10, the diameter, resistance or weight of any other size of wire in the table can be approximated, if the tables are not at hand. No. 10 is a convenient size to memorize, since its diameter is about $\frac{1}{10}$ inch and its area is about 10,000 circular mils.

The size, weight and resistance of the B. & S. sizes of solid wire in general use in distribution are given in Table No. XVI and similar data for stranded cables up to 2,000,000 circular mils in Table No. XVII.

TABLE XVI. — PROPERTIES OF SOLID COPPER WIRE.

| No. B. & S. | Bare diam., mils. | Area, cir. mils. | Weight. | | | | Resistance at 68 deg. F. | |
|---|---|---|---|---|---|---|---|---|
| | | | Per 1000 ft. | Per mile. | Per 1000 ft., weatherproof. | Feet per lb. | Per 1000 ft. | Per mile. |
| 0000 | 460 | 211,600 | 640.5 | 3381 | 741 | 1.561 | .0489 | .2583 |
| 000 | 409.6 | 167,800 | 508 | 2682 | 598 | 1.961 | .0617 | .3258 |
| 00 | 364.8 | 133,100 | 403 | 2127 | 485 | 2.482 | .0778 | .4108 |
| 0 | 324.9 | 105,500 | 319.5 | 1687 | 382 | 3.13 | .0981 | .5180 |
| 1 | 289.3 | 83,690 | 253.3 | 1337 | 312 | 3.947 | .1237 | .6531 |
| 2 | 257.6 | 66,370 | 201 | 1062 | 254 | 4.977 | .156 | .8237 |
| 3 | 229.4 | 52,630 | 159.3 | 841 | 199 | 6.276 | .1967 | 1.039 |
| 4 | 204.3 | 41,740 | 126.4 | 667 | 163 | 7.914 | .248 | 1.309 |
| 5 | 181.9 | 33,100 | 100.2 | 529 | 132 | 9.98 | .3128 | 1.652 |
| 6 | 162 | 26,250 | 79.5 | 420 | 109 | 12.58 | .3944 | 2.082 |
| 7 | 144.3 | 20,820 | 63.02 | 333 | 88 | 15.87 | .4973 | 2.626 |
| 8 | 128.5 | 16,510 | 49.98 | 264 | 74 | 20.01 | .6271 | 3.311 |
| 9 | 114.4 | 13,090 | 39.63 | 209 | 60 | 25.23 | .7908 | 4.175 |
| 10 | 101.9 | 10,380 | 31.43 | 166 | 50 | 31.82 | .9972 | 5.265 |
| 11 | 90.7 | 8,234 | 24.93 | 132 | 42 | 40.12 | 1.257 | 6.637 |
| 12 | 80.8 | 6,530 | 19.77 | 104.4 | 34 | 50.59 | 1.586 | 8.374 |
| 13 | 71.96 | 5,178 | 15.68 | 82.8 | ........ | 63.78 | 2.00 | 10.56 |
| 14 | 64.08 | 4,107 | 12.43 | 65.6 | 24 | 80.44 | 2.52 | 13.31 |
| 15 | 57.07 | 3,257 | 9.86 | 52.05 | ........ | 101.4 | 3.179 | 16.78 |
| 16 | 50.82 | 2,583 | 7.82 | 41.28 | 19 | 127.9 | 4.01 | 21.17 |

TABLE XVII. — PROPERTIES OF STRANDED COPPER CABLES.

| No. B. & S. | Bare diam., mils. | Area, cir. mils. | Weight. | | | | Resistance at 68 deg. F. | |
|---|---|---|---|---|---|---|---|---|
| | | | Per 1000 ft. | Per mile. | Per 1000 ft., weather-proof. | Feet per lb. | Per 1000 ft. | Per mile. |
| ...... | ........ | 2,000,000 | 6,100 | 32,208 | ......... | .164 | .00518 | .02733 |
| ...... | ........ | 1,500,000 | 4,575 | 24,156 | 5,335 | .219 | .00690 | .03644 |
| ...... | 1,152 | 1,000,000 | 3,050 | 16,104 | 3,610 | .328 | .01035 | .05466 |
| ...... | 1,000 | 750,000 | 2,288 | 12,078 | 2,730 | .437 | .0138 | .0729 |
| ...... | 819 | 500,000 | 1,525 | 8,052 | 1,870 | .655 | .0207 | .1093 |
| ...... | 728 | 400,000 | 1,220 | 6,442 | 1,529 | .819 | .0259 | .1366 |
| ...... | 679 | 350,000 | 1,068 | 5,636 | 1,320 | .936 | .0296 | .1562 |
| ...... | 630 | 300,000 | 915 | 4,831 | 1,133 | 1.093 | .0345 | .1822 |
| ...... | 590 | 250,000 | 762 | 4,026 | 940 | 1.312 | .0414 | .2186 |
| 0000 | 530 | 211,600 | 645 | 3,405 | 779 | 1.55 | .0489 | .2583 |
| 000 | 470 | 167,800 | 513 | 2,709 | 650 | 1.95 | .0617 | .3258 |
| 00 | 420 | 133,100 | 406 | 2,144 | 527 | 2.46 | .0778 | .4108 |
| 0 | 375 | 105,500 | 322 | 1,700 | 430 | 3.11 | .0981 | .518 |
| 1 | 330 | 83,690 | 255 | 1,347 | 326 | 3.94 | .1237 | .653 |
| 2 | 291 | 66,370 | 203 | 1,072 | 270 | 4.93 | .1560 | .824 |
| 3 | 261 | 52,630 | 160 | 845 | 218 | 6.25 | .1967 | 1.039 |
| 4 | 231 | 41,740 | 127 | 671 | 176 | 7.87 | .2480 | 1.309 |

**Physical Properties.** — The general physical properties of hard and annealed copper wire are shown in Table No. XVIII.

TABLE XVIII. — PHYSICAL PROPERTIES OF VARIOUS METALS.

| | Copper, annealed. | Copper, hard. | Aluminum. | Iron. | Steel. |
|---|---|---|---|---|---|
| Per cent conductivity....... | 100 | 98 | 62.1 | 16.8 | 12.2 |
| Specific gravity............. | 8.9 | 8.94 | 2.68 | 7.8 | 7.85 |
| Lbs. per cu. ft............... | 555 | 558 | 167 | 487 | 490 |
| Lbs. per cu. in.............. | .321 | .323 | .0967 | .282 | .284 |
| Breaking strength, lbs. per sq. in.................... | 34000 | 55000 | 26000 | 55000 | 68000 |
| Coeff. of exp. per deg. C..... | .0000171 | .0000171 | .0000231 | .00012 | .00012 |
| Coeff. of exp. per deg. F..... | .0000095 | .0000095 | .0000128 | .000067 | .000067 |
| Melting point, deg. C........ | 1050 | 1050 | 625 | 1600 | 1475 |
| Melting point, deg. F........ | 1920 | 1920 | 1157 | 2910 | 2685 |

Hard copper wire is that which is left in the condition in which it comes from the drawing die. In this condition the surface of the wire is very hard, and its tensile strength is much higher

than it is after annealing. Its electrical conductivity is 98 per cent of annealed or soft copper.

The tensile strength of annealed copper wire varies from 32,000 to 36,000 pounds per square inch, depending upon the degree of annealing, while that of hard copper wire varies from 45,000 to 65,000 pounds per square inch.

**Aluminum.** — The properties of aluminum wire are of importance where it is used in transmission work. From the characteristics shown in Table No. XVIII it may be seen that though its conductivity is but 62 per cent, its specific gravity is only 30 per cent of that of copper. The weight per foot of an aluminum conductor having the same resistance is therefore $\frac{30}{62}$ = 48 per cent of that of a copper wire.

TABLE XIX. — PROPERTIES OF STRANDED ALUMINUM CABLES.

| No. B. & S. | Bare diam, mils. | Area, circular mils. | Weight. | | | | Resistance at 68 deg. F. | |
|---|---|---|---|---|---|---|---|---|
| | | | Per 1000 ft. | Per mile. | Per 1000 ft., weatherproof. | Bare feet per lb. | Per 1000 ft. | Per mile. |
| ...... | 1.15 | 1,000,000 | 920 | 4,858 | 1,408 | 1.087 | .01695 | .0895 |
| ...... | 1.00 | 750,000 | 690 | 3,645 | 1,067 | 1.45 | .0226 | .1193 |
| ...... | .81 | 500,000 | 460 | 2,430 | 740 | 2.04 | .033 | .179 |
| ...... | .73 | 400,000 | 368 | 1,944 | 567 | 2.72 | .0424 | .224 |
| ...... | .68 | 350,000 | 322 | 1,701 | 502 | 3.11 | .0484 | .256 |
| ...... | .63 | 300,000 | 276 | 1,458 | 436 | 3.62 | .0565 | .298 |
| ...... | .58 | 250,000 | 230 | 1,215 | 375 | 4.35 | .0678 | .358 |
| 4–0 | .54 | 211,600 | 195 | 1,028 | 280 | 5.73 | .08 | .423 |
| 3–0 | .47 | 167,800 | 154 | 816 | 232 | 6.48 | .101 | .533 |
| 2–0 | .42 | 133,100 | 122 | 647 | 192 | 8.16 | .127 | .673 |
| 0 | .37 | 105,500 | 97.1 | 513 | 155 | 10.3 | .160 | .847 |
| 1 | .33 | 83,690 | 77 | 407 | 132 | 13. | .202 | 1.069 |
| 2 | .30 | 66,270 | 61 | 323 | 108 | 16.4 | .255 | 1.35 |
| 3 | .26 | 52,630 | 48.5 | 256 | 88 | 20.6 | .322 | 1.70 |
| 4 | .23 | 41,740 | 38.5 | 203 | 72 | 26. | .406 | 2.144 |

The tensile strength is about two-thirds that of soft copper and about half that of hard copper. The cross-section of the aluminum conductor, being 50 per cent greater than the

equivalent copper conductor, its actual breaking strength is about the same as the copper conductor having equal conductivity. The weight, however, being only half that of copper, of equal conductivity, its tensile factor of safety in a span of given deflection is higher than that of copper. This characteristic, together with the greater ease of handling in remote sections, has led to the general use of aluminum in transmission lines. The weights of aluminum and copper being as 48 to 100, the price per pound is about as 100 to 48 for equal cost and equal conductivity. The weights and resistances of the common sizes of stranded aluminum wires and cables are given in Table No. XIX.

**Iron and Steel.** — Iron and steel wire is used in electrical distribution work chiefly for guying purposes, or in special situations where long spans require high tensile strength. It is used to a limited extent for distributing conductors where the investment must be kept small and where the current carried is not great. Its mechanical properties are therefore those which chiefly concern the electric light and power engineer, and they are included in Table No. XVIII together with the electrical properties.

**Energy Loss.** — The flow of electricity along a conductor is accompanied by a loss of energy which is proportional to the square of the current in amperes and the resistance of the circuit. This may be written watts loss = $C^2R$, $C$ being the current flowing and $R$ the resistance of the circuit. The loss in a circuit having a resistance of .1 ohm when it is carrying a load of 100 amperes is $100 \times 100 \times .1 = 1000$ watts. The energy absorbed by the resistance of the circuit is dissipated in the form of heat, which elevates the temperature of the conductor in proportion to the energy absorbed and to the facility with which the heat may be radiated. The maximum

current carrying capacity of a conductor of given size is therefore dependent upon whether it is installed in open air, in moulding, iron conduit or underground. The character of the insulation is also a factor, since certain insulations may be safely operated at higher temperatures than others. Weatherproof insulation may be safely operated at higher temperatures than rubber, while bare wire may be operated at much higher temperatures than any of the usual forms of insulation will withstand.

**Current Carrying Capacity.** — The allowable limits of operation for various conditions must be known with reasonable accuracy if the conductors are to be kept in good condition.

If the maximum allowable temperature is known for any class of circuits the maximum current which the circuit may carry under the given condition may be calculated from the following formula:

$C = A\sqrt{\frac{TD^3}{1.8\,r}}$, in which $T$ is the rise in temperature, $D$ is the diameter of the conductor in inches (not including insulation), $r$ is the specific resistance per mil foot at the final temperature, and $A$ is a constant which varies with the character of the insulation and method of installation as follows:

| | |
|---|---|
| Bare wire in open air | $A$ is 1100 |
| Bare wire indoors | $A$ is 600 |
| Rubber-covered wire indoors | $A$ is 500 |
| Underground cable, rubber insulation, single conductor | $A$ is 500 |
| Underground cable, paper or cloth, single conductor | $A$ is 550 |
| Underground cable, rubber insulation, three conductor | $A$ is 380 |
| Underground cable, paper or cloth, three conductor | $A$ is 330 |

The values of $r$, the specific resistance, at various temperatures, are shown in the curve in Fig. 131.

With a circuit of No. 0 bare copper wire in open air, in which it is permissible to allow the temperature to rise from 70 to 120 degrees F., $D$ is .325, $T$ is 50, $r$ is 11.6 and $A$ is 1100. The current which would produce this rise in temperature is $C = 1100 \sqrt{\frac{50 \times (.325)^3}{1.8 \times 11.6}} = 310$ amperes. The same wire indoors could be loaded to $\frac{600}{1100} \times 310 = 170$ amperes, or in an underground single-conductor paper cable to $\frac{550}{1100} \times 310 = 155$ amperes.

The use of such a formula is somewhat cumbersome, and it is more convenient to have tables showing the current carrying capacity of the various sizes of conductors under different conditions.

The safe carrying capacity of the sizes of conductors commonly used in distribution work is therefore given in Table No. XX. These are the values permitted by the National Electric Code in interior work and they may be exceeded somewhat in outdoor or underground construction.

TABLE XX. — CURRENT CARRYING CAPACITY OF COPPER CONDUCTORS.

| No. B. & S. | Rubber. | Weatherproof. | No. B. & S. | Rubber. | Weatherproof. |
|---|---|---|---|---|---|
| 14 | 12 | 16 | 2–0 | 150 | 220 |
| 12 | 17 | 23 | 3–0 | 177 | 262 |
| 10 | 24 | 32 | 4–0 | 210 | 312 |
| 8 | 33 | 46 | 250,000 | 235 | 350 |
| 6 | 46 | 65 | 300,000 | 270 | 400 |
| 5 | 54 | 77 | 350,000 | 300 | 450 |
| 4 | 65 | 92 | 400,000 | 330 | 500 |
| 3 | 76 | 110 | 500,000 | 390 | 590 |
| 2 | 90 | 131 | 750,000 | 525 | 800 |
| 1 | 107 | 156 | 1,000,000 | 650 | 1,000 |
| 0 | 127 | 185 | 1,500,000 | 850 | 1,360 |
| ........ | ........ | ........... | 2,000,000 | 1,050 | 1,670 |

**Voltage Drop.** — The transmission of electricity over a conductor is accompanied by a loss of pressure due to its resistance. The scientist Ohm discovered that this loss was $E = C \times R$, when $C$ is the current flowing and $R$ the resistance of the conductor. This has been called Ohm's law, and it is strictly true only for direct-current circuits.

A simple electric-lighting circuit is composed of two elements, the conductors leading to the lamp and the lamp itself. The current passing through the circuit is the same in both elements, but the resistances of the conductors and the lamp are different, and the fall of pressure as the current passes on its way through the circuit is directly proportional to these resistances.

The function of the conductor being to convey the supply of electricity from its source to the consuming device, it is desirable that as little pressure be absorbed by the resistance of the conductor as possible.

**Calculation of Circuits.** — The problem of designing a circuit is therefore one of determining what size of conductor should be used to limit the loss of voltage to a specified amount, when the distance and current to be carried have been determined.

The resistance of a mil foot of copper at 68 degrees F. being 10.4 ohms, that of a conductor $D$ feet long and $M$ circular mils in area is $R = \frac{D \times 10.4}{M}$. The drop with current $C$ is therefore $E = CR = \frac{C \times D \times 10.4}{M}$ or $M = \frac{C \times D \times 10.4}{E}$. If both conductors are of the same size the total drop is $E = \frac{2\,D \times C \times 10.4}{M}$. If they are not of the same size, the drop in the different sizes must be figured separately, and added together.

For example, assume that a two-wire circuit is to carry a load of 100 amperes at a distance of 300 feet with a drop of five volts, what size of conductor must be used?

$$M = \frac{2\,D \times C \times 10.4}{E} = \frac{2 \times 300 \times 100 \times 10.4}{5} = 124{,}800 \text{ c.m.},$$

which is found by reference to Table XVI to be the nearest the cross-section of No. 00 B. & S. which should be used.

If a circuit of No. 4/0 wire is to carry 100 amperes 500 feet, what will the voltage drop be? In Table XVI No. 4/0 has an area of 211,600 circular mils, and $E = \frac{2 \times 500 \times 100 \times 10.4}{211{,}600} = 4.9$ volts.

The calculation of such problems can be simplified where the size of the circuit is already fixed by the use of the values of resistance per 1000 feet given in Table XVI. For instance, in the case of the 500-foot circuit of No. 4/0 wire, the resistance per 1000 feet is .0489 ohm, the circuit being .5 thousand feet long, $E = C \times R = 100 \times .0489 \times .5 \times 2 = 4.9$ volts. This operation involves only multiplication, and the calculation is therefore somewhat more simple.

The use of a table is not always convenient, but when this method is used regularly, it becomes an easy matter to memorize the resistance of a few principal sizes, from which it is easy to find the odd sizes by applying the law of the B. & S. wire gauge table.

**Three-wire Circuits.** — In applying calculations to a three-wire Edison circuit, separate computations must be made for each conductor if the load is appreciably unbalanced.

For example, if a circuit having two 4/0 outers and a No. 0 neutral 1000 feet long carries a load of 150 amperes on the positive side and 110 on the negative, the drop will be found as follows:

Resistance of 1000 feet of 4/0 = .05 ohm and that of No. 0 = .1 ohm.

$E = CR = 150 \times 0.5 = 7.5$ volts on positive wire.

$E = CR = 110 \times .05 = 5.5$ volts on negative wire.

$E = CR = 40 \times .1 = 4$ volts on neutral wire.

The neutral wire drop must be added to the drop on the heavy side and subtracted from that on the lighter side. If the pressure of the supply is 120 volts on each side, the pressure at the other end will be 120 less 11.5 = 108.5 on the positive side, and 120 less 1.5 = 118.5 on the negative side. These relations are shown graphically in Fig. 132 (a).

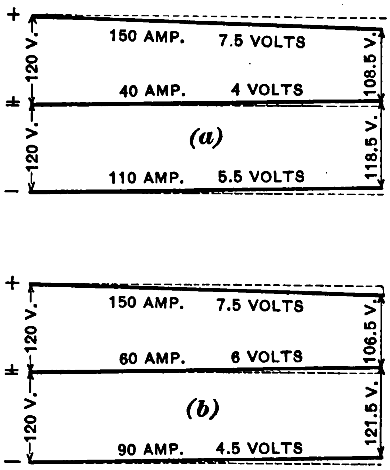


Fig. 132. Voltage Drop in Three-wire Circuit.

This example illustrates the importance of keeping three-wire mains approximately balanced. It also indicates the necessity of having the neutral of ample size so as not to emphasize unbalanced conditions when they exist. In this case, if the neutral had been of 4/0 the drop on it would have been 2 volts; the pressure on the positive side at the far end would have been 110.5 volts, with 116.5 on tne negative.

When the conditions are such that the drop on the neutral conductor exceeds that on the lighter loaded side, the pressure on the lighter side at the far end is higher than the pressure at the source of supply. This condition is illustrated in Fig. 132 (b), and is one which is sometimes found in practice on branches where the load consists of a few two-wire con-

sumers whose hours of use are so irregular that they cannot be arranged to balance each other at all times.

In this case the outsides are 4/0 and the neutral No. 0.

The drop on the positive at 150 amperes is 7.5 volts.

The drop on the negative at 90 amperes is 4.5 volts.

The drop on the neutral at 60 amperes is 6 volts.

With 120 volts at the point of supply the pressure at the far end is 120 less $(7.5 + 6)$ volts $= 106.5$ volts on the positive side, while on the negative side it is 120 less 4.5 volts plus 6 volts $= 121.5$ volts, or 1.5 volts higher than at the point of supply.

## CHAPTER XIV.

## ALTERNATING-CURRENT CIRCUITS.

The laws governing the loss of potential in direct-current circuits apply to alternating-current circuits only as regards the loss due to resistance.

In an alternating-current circuit fall of potential is caused by two physical conditions: (a) *resistance*, and (b) *reactance*, due to self-induction.

The component of drop due to resistance is governed by the same laws which govern direct-current circuits. This component is directly opposed to the current flowing in the circuit and as in direct-current circuits $E = CR$.

**Inductive Reactance.** — The component of drop due to self-inductive reactance is a counter electromotive force set up in the circuit by the current flowing through it. The magnetic field of the circuit, reversing with each alternation, induces an electromotive force in it, which lags a quarter cycle behind the magnetic field and the current wave. The resistance drop being directly opposed to the current and the reactance drop being a quarter cycle behind it, their relation may be represented by two sides of a right-angled triangle, as in Fig. 133. The line $OC$ represents the resistance drop in 1000 feet of No. 6 wire, and the line $CD$ represents the reactance drop in the same length

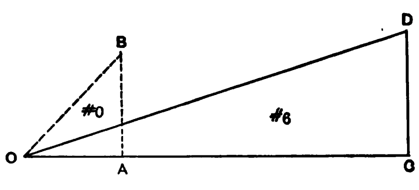


Fig. 133. Resistance and Reactance of No. 6 and No. 0.

of wire. The resultant $OD$ of these two influences is called the *impedance.* The reactance of an electric current varies with the frequency of the current flowing in the circuit and with the number of lines of force linked with the circuit for each ampere of current flowing in it. The reactance of a given circuit is therefore more when it carries current at 60 cycles than at 25 cycles. Similarly, reactance is increased by the separation of the conductors of a circuit or by the introduction of iron into the magnetic field, since either of these increase the number of lines of force linked by the circuit.

For this reason if alternating-current circuits are to be installed in iron pipe, all conductors of the circuit must be carried in the same pipe so that the entire magnetic field will be within the pipe and will not be affected by the presence of the iron. With overhead circuits there is no iron in the magnetic field and the only means of varying the reactance is by changing the distance between opposite polarities or the frequency.

**Calculation of Inductive Reactance.** — The inductive reactance of a single-phase circuit is $X = \frac{2\,d \times 6.28 \times L \times f}{1000}$ ohms, in which $L$ is the coefficient of self-induction in millihenrys per 1000 feet of wire, $F$ is the frequency and $d$ is the length in thousands of feet.

The coefficient of self-induction of parallel wires of non-magnetic metal, strung in open air and without iron in the magnetic field, may be calculated from the formula

$$L = .14 \log \frac{D - r}{r} + .0152 \text{ millihenrys per 1000 feet of wire,}$$

in which $D$ is the distance between centers of the conductors and $r$ is the radius of the conductor.

For a circuit of No. 0 wire strung 12 inches apart

$$L = .14 \log \frac{12 - .162}{.162} + .0152 = .277 \text{ millihenry.}$$

At 60 cycles,

$$X = \frac{6.28 \times 60\, L}{1000} = .377\, L = .1043 \text{ ohm per 1000 feet of wire.}$$

At 25 cycles,

$$X = \frac{6.28 \times 25\, L}{1000} = .157\, L = .0434 \text{ ohm per 1000 feet of wire.}$$

The reactance at any other frequency is in direct proportion to the ratio of the frequencies.

From the formula for self-induction it is apparent that the effect of the separation of the wires does not vary directly with the distance of separation.

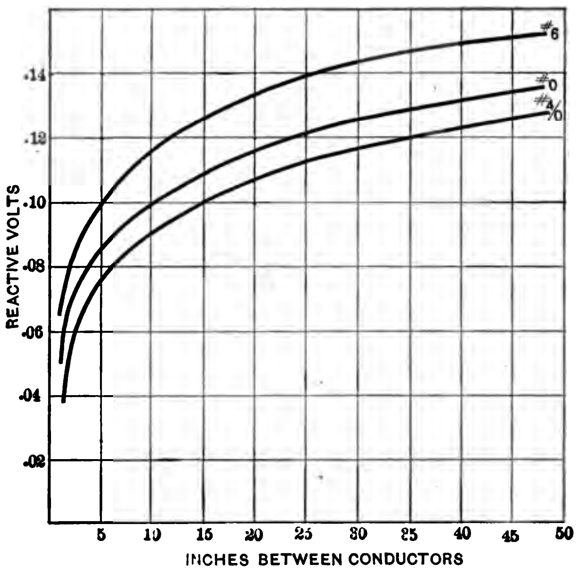



Fig. 134. Relation of Reactance to Separation of Conductors.

For instance, when $D$ is 2 inches the value of $\frac{D-r}{r}$ for No. 0 wire is $\frac{2 - .162}{.162} = 11.3$ and the value of the logarithm is 1.054. At 12 inches, $\frac{D-r}{r}$ is 73.2 and the logarithm is 1.87.

The reactance varies as 1.054 is to 1.87, while the distance has been increased to six times its former values.

The rate of change of the reactance as the distance between centers is varied is shown for a few principal sizes of conductor by the curves in Fig. 134. These are based on the values of reactance given in Table XXI.

TABLE XXI. — REACTANCE PER 1000 FEET OF CONDUCTOR AT 60 CYCLES.

| Size. | Volts per ampere. | | | | | | Resistance at 68 deg. F. |
|---|---|---|---|---|---|---|---|
| | Distance between centers. | | | | | | |
| | ½ in. | 1 in. | 2 in. | 3 in. | 6 in. | 12 in. | |
| 1,000,000 | ........ | ........ | ...... | ...... | .063 | .0784 | .01035 |
| 500,000 | ........ | ........ | ...... | ...... | .071 | .0864 | .0207 |
| 350,000 | ........ | ........ | ...... | ...... | .0746 | .0905 | .0296 |
| 0000 | .0328 | .0394 | .0553 | .0646 | .0805 | .0964 | .0489 |
| 000 | .0355 | .0421 | .058 | .067 | .0832 | .0991 | .0617 |
| 00 | .0381 | .0447 | .060 | .070 | .0858 | .1017 | .0778 |
| 0 | .0408 | .0474 | .0633 | .0726 | .0885 | .1043 | .0981 |
| 1 | .0435 | .0501 | .0659 | .0752 | .0911 | .107 | .1237 |
| 2 | .0461 | .0527 | .0686 | .0779 | .0938 | .1097 | .156 |
| 4 | .0514 | .0580 | .0739 | .0832 | .0991 | .1150 | .248 |
| 6 | .0567 | .0633 | .0792 | .0885 | .1044 | .1203 | .394 |
| 8 | .0621 | .0687 | .0845 | .0938 | .1097 | .1256 | .627 |
| 10 | .0674 | .074 | .0898 | .0991 | .1151 | .1309 | .997 |

| Size. | 18 in. | 24 in. | 36 in. | 48 in. | 60 in. | 72 in. |
|---|---|---|---|---|---|---|
| 1,000,000 | .0877 | .0943 | .1036 | .1102 | .1153 | .1194 |
| 500,000 | .0957 | .1023 | .1116 | .1182 | .1233 | .1274 |
| 350,000 | .0998 | .1064 | .1157 | .1223 | .1274 | .1316 |
| 0000 | .1057 | .1123 | .1216 | .1282 | .1333 | .1374 |
| 000 | .1084 | .1150 | .1242 | .1308 | .1360 | .1401 |
| 00 | .1110 | .1176 | .1269 | .1335 | .1386 | .1427 |
| 0 | .1136 | .1202 | .1295 | .1361 | .1412 | .1454 |
| 1 | .1163 | .1229 | .1322 | .1388 | .1439 | .1481 |
| 2 | .1190 | .1256 | .1348 | .1414 | .1466 | .1507 |
| 4 | .1243 | .1309 | .1402 | .1468 | .1519 | .1561 |
| 6 | .1296 | .1362 | .1455 | .1521 | .1572 | .1613 |
| 8 | .1349 | .1415 | .1508 | .1574 | .1625 | .1667 |
| 10 | .1402 | .1468 | .1561 | .1627 | .1678 | .1720 |

It is seen that the reactance increases rapidly as the separation is increased up to six inches and then less and less rapidly as further separation is produced.

This is a fortunate condition for overhead transmission lines operating at high voltages which require large separations to guard against short circuits.

It is also a fortunate fact that in underground cables distributing heavy low-potential currents the conductors can be brought close together inside of one lead sheath, thus minimizing the inductive component of line drop.

In the operation of alternating current series arc lighting circuits with extended open loops trouble is sometimes experienced with excessive induction in telephone circuits which pass through such loops. This trouble is obviated by the use of parallel loops, as described in Chapter I.

The calculation of the values of reactance is not convenient when logarithms are not readily available and is rather laborious in any event. The work is simplified by the use of the values of reactance given in Table XXI. This table gives the reactance in volts per ampere for 1000 feet of conductors for the distances of separation and sizes of wire commonly used in transmission and distribution work.

For example, assuming a single-phase circuit 10,000 feet long operating at 60 cycles and carrying a load of 100 amperes, with No. 0 wires 12 inches apart, what are the values of the inductive and ohmic components of the impedance?

The reactance per 1000 feet per ampere for No. 0 wire 12 inches apart is $X = .1043$. The resistance from Table XXI is .098 ohm per 1000 feet. The inductive component of the impedance of the circuit is

$$X = 2\,d \times C \times .1043 = 2 \times 10 \times 100 \times .1043 = 208 \text{ volts.}$$

The ohmic component is $R = 2 \times 10 \times 100 \times .098 = 196$ volts.

The impedance drop of the circuit is $\sqrt{(208)^2 + (196)^2} = 286$ volts.

The length of the line $OA$ in Fig. 133 is proportional to the resistance component, that of $AB$ represents the inductive component and $OB$ the resultant of the two. If the circuit were of two No. 6 wires the resistance component would be 788 volts, the inductive component 240 volts; and the impedance drop would be $\sqrt{(788)^2 + (240)^2} = 824$ volts.

This condition is represented by $OC$ and $CD$ in Fig. 133. It will be seen from these examples that the inductive component of drop in a No. 6 wire is only about 40 per cent greater than that of the No. 0 circuit, although its resistance is nearly four times that of the No. 0 circuit. It is further apparent that the ratio of resistance to inductance decreases greatly as the size of wire is increased. On this account increasing the area of alternating-current conductors for the purpose of reducing the pressure drop becomes less effective after the size is increased above the point where the resistance is about equal to the inductance. At 60 cycles this is at about No. 0 for overhead circuits, and at 250,000 to 300,000 c.m. for underground cables. At 25 cycles No. 0000 to 250,000 c.m. may be used for overhead lines, and sizes up to 1,000,000 are effective in underground cables. For instance, in the 10,000 feet No. 0 circuit above referred to, the ohmic drop is 196 volts and the inductive component is 208 volts at 100 amperes. If this circuit were required to carry 200 amperes it could be replaced by 4/0 cable or supplemented by the addition of another circuit of No. 0. If a 4/0 circuit were substituted, the ohmic drop would be 196 volts as before, but the inductive drop would be 384 volts. With two No. 0 circuits the drop would remain the same, 196 volts ohmic and 208 volts inductive.

Where the drop can be compensated for properly, or where the circuit is so short that the increased drop is negligible, the

larger sizes might be used, but where line drop is the limiting feature, two or more circuits of the smaller wire are preferable.

**Resistance and Inductance Factors.** — The *resistance factor* of a circuit is the ratio of its resistance to its impedance. Likewise the *inductance factor* is the ratio of the inductance to the impedance.

In the No. 0 circuit used above, for example, the resistance factor is $\frac{196}{286} = .685$ and the inductance factor is $\frac{208}{286} = .727$.

The resistance and inductance factors of a circuit vary with the size of wire and with the distance of separation. At 60 cycles the resistance factor is the higher for the sizes of conductor smaller than No. 0 and the inductance factor is the higher for the sizes of conductor larger than No. 0.

When the resistance factor is known the inductance factor is $\sqrt{1 - (\text{Resistance factor})^2}$, and *vice versa*. In other words, $(\text{Resistance factor})^2 + (\text{Inductance factor})^2 = 1$.

The power consumed in a circuit is the product of the current by the impedance volts and by the resistance factor. If the loop forming a circuit were closed at the remote end, the power factor of the circuit would be the same as its resistance factor.

The values of inductance factor which correspond to various common values of resistance (or power) factor appear in the following table:

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Resistance (or power) factor | 50 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 97.5 | 100 |
| Inductance factor | 80.5 | 80 | 76 | 71 | 66 | 60 | 53 | 44 | 31 | 22.2 | 0 |

**Calculation of Line Pressure Drop.** — The total pressure drop in a circuit is determined from the resistance and inductance components in conjunction with the power factor of the load which the circuit is carrying. The drop is greatest at power factors which are near the resistance factor of the circuit. If a certain load draws 100 amperes at 70 per cent

power factor over a No. 0 circuit having a resistance factor of 68.5 per cent, the net fall of pressure between the point of supply and point of delivery will be greater than it is with the same current on the circuit at 100 per cent power factor.

Referring to Fig. 135, let the line *OE* represent the pressure delivered at the terminals of an induction motor. *OR* is the component of *OE*, which is doing useful work. *ER* is the wattless component of self-induction which causes the current through the motor to be out of phase with the impressed voltage.

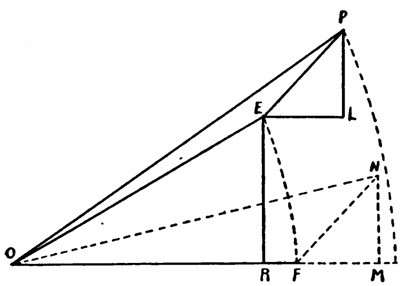



Fig. 135. Effect of Power Factor on Line Drop.

*EL* is the resistance component and *LP* is the inductive component of the line drop. The resistance component of the line drop *EL* and the power component of the impressed voltage *OR* are in phase with each other and the inductive components *ER* and *LP* are in phase with each other.

The resultant *OP* is the bus pressure necessary to deliver a pressure *OE* at the motor terminals. The net line drop is therefore the difference between *OP* and *OE*.

With noninductive load, such as incandescent lamps, *ER* disappears and the impressed pressure on the lamps takes the position of *OF* (= *OE*). The generated pressure necessary to deliver *OF* at the lamps is *ON* and the drop is the difference between *ON* and *OF*.

For example, assume an inductive load of 100 amperes at 2200 volts single phase, delivered at the end of a two-wire line of No. 0 wire 4500 feet long with wires 12 inches apart, a frequency of 60 and a power factor of 80 per cent. The power factor of the load being 80 per cent, we find by reference to the above table that the corresponding inductance factor is 60 per cent.

$$OR \text{ is } .80 \times 2200 = 1760 \text{ volts.}$$

$$ER \text{ is therefore } .6 \times 2200 = 1320 \text{ volts.}$$

By reference to Table XXI we find that the resistance drop per 1000 feet per ampere for No. 0 is .098 volt. Hence the resistance drop is $.098 \times 4.5 \times 100 = 44.0$ volts for each wire. There being two wires $EL$ is $2 \times 44 = 88$ volts.

Similarly, the inductive drop per 1000 feet per ampere for 12-inch centers is .104 volt and $LP$ is $2 \times .104 \times 4.5 \times 100 = 93$ volts. The power and resistance component is $OR + EL$ or $1760 + 88 = 1848$ volts and the inductive component is $ER + LP$ or $1320 + 93 = 1413$ volts.

The resultant of these, $OP$, is

$$\sqrt{(1848)^2 + (1413)^2} = 2332 \text{ volts.}$$

This is the pressure necessary to deliver 2200 volts at the end of the line. The drop is therefore the difference, or 132 volts, with a load of 100 amperes at 80 per cent power factor.

If a lighting load of 100 amperes at 100 per cent power factor were being carried, the inductance factor $ER$ is zero, and $ON$ is

$$\sqrt{(2290)^2 + (93)^2} = 2292 \text{ volts.}$$

The drop is therefore 92 volts, with a load of 100 amperes at 100 per cent power factor.

**Mershon Method.** — The calculations required for the solution of practical problems is rather cumbersome. Mershon has therefore devised a diagram by which the calculations

may be made with much greater facility and yet with sufficient accuracy for all ordinary purposes.

This diagram is presented in Fig. 136 and is based on the principles of the diagram of Fig. 135. The concentric circles are described about a center off the diagram which corresponds to the point o in Fig. 135. The divisions are made in percentages so as to make the scale applicable to all voltages.

The use of the chart may be illustrated by the foregoing circuit of No. 0, carrying a load of 100 amperes at a distance of 4500 feet. The ohmic drop, being 88 volts, is 4 per cent, while the inductive drop is 4.2 per cent. The power factor was assumed at 80 per cent, or .8. The base of the .8 power factor line in Fig. 136 is the point *R* in Fig. 135. The point where the .8 power factor line intersects the first circle is the point *E* in Fig. 135. Passing to the right 4 divisions and then up 4.2 divisions a point is reached which is about midway between the 5 per cent and 6 per cent circles. This point is equivalent to the point *D* in Fig. 135. The pressure necessary to deliver 100 per cent pressure at the end of the circuit is 105.5 per cent. The drop is therefore 5.5 per cent of 2200, or 121 volts. The result may be gotten more accurately if desired by multiplying the percentages of drop by two or three before applying them to the diagram, and then dividing the result by the same multiplier. For instance, multiplying by three in this case, the ohmic drop is 12 per cent and the inductive drop is 12.9 per cent. Passing to the right 12.0 divisions and upward 12.9 divisions, we reach a point corresponding to 17.5 per cent. Dividing by three the drop is 5.8 per cent, or 128 volts, as compared with 132 volts determined by calculation.

If the load on the circuit has a power factor of 100 per cent one begins at the base of the 100 per cent P.F. line, passes to the right 12.0 divisions and up 12.9 divisions. The point

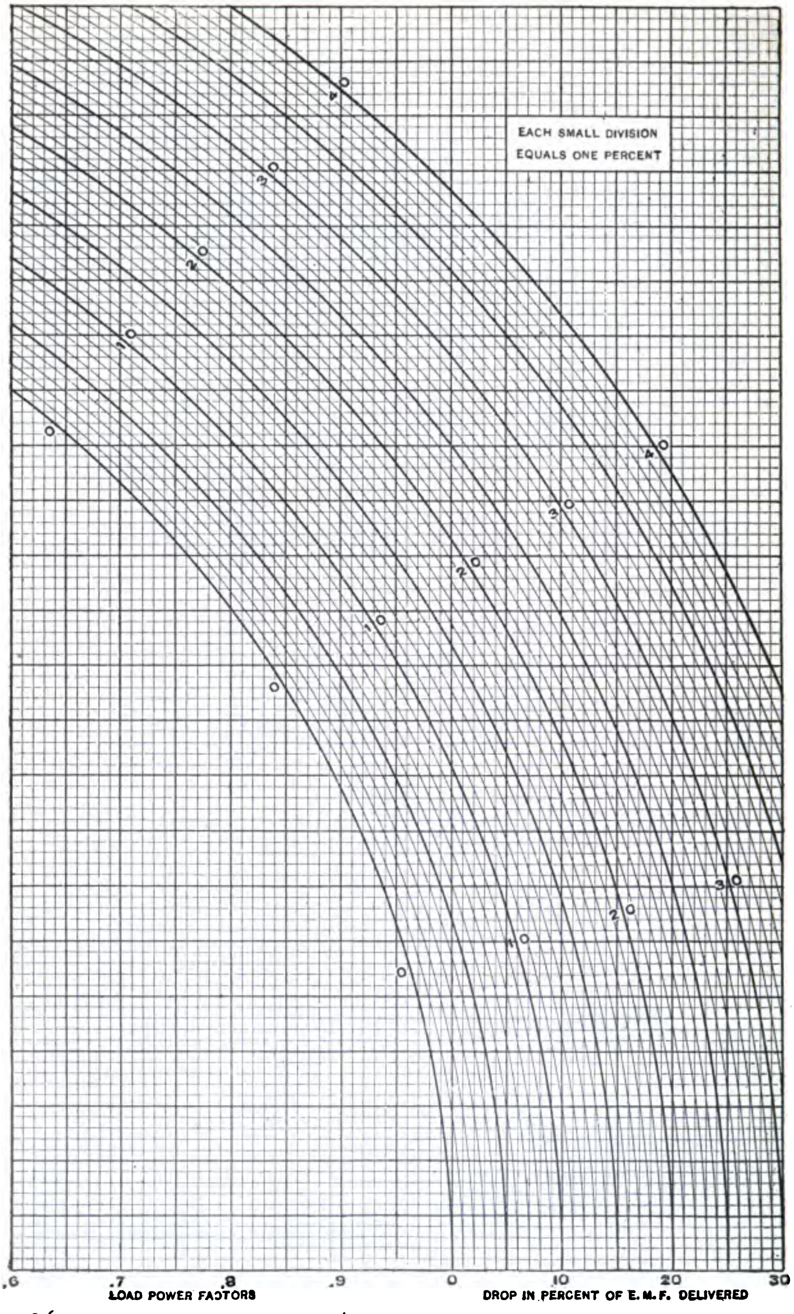





Fig. 136. Mershon Diagram for Calculation of Line Drop.

is on the 13 per cent circle. Dividing by three the drop is 4.33 per cent, or about 93 volts, as compared with 92 volts calculated.

**Two-phase Feeder Drop.** — In the case of a two-phase four-wire circuit the drop is figured for one wire and multiplied by two, as in the case of the single-phase circuit.

With a three-wire two-phase system having the load connected between the outers and neutral, the inductive drop

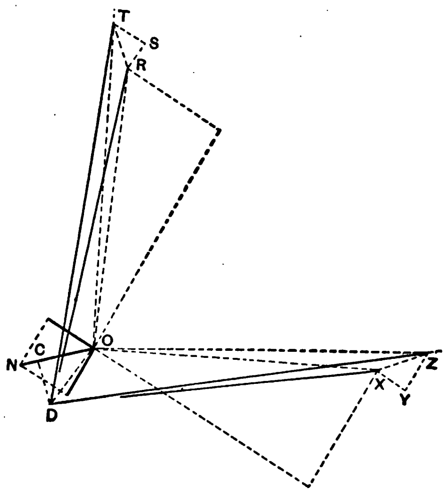



Fig. 137. Drop on Two-phase Three-wire Circuit.

on the neutral wire tends to produce an unbalanced condition of pressure at the feeder end. The inductive component is nearly in phase with the resistance component of one of the outer wires and nearly at right angles with the other. This condition is illustrated in the diagram in Fig. 137. The drop on the outer wires is represented by the triangles *XYZ* and *RST*. *ON* represents the phase of the neutral current and *OCD* represents the ohmic and inductive drops on the neutral conductor. The power factor of the load is assumed at 90

per cent. The voltage necessary to maintain normal pressure at the feeder end is represented by line *DZ* on one phase and by *DT* on the other phase. The drop is the difference between *DZ* and *OX* in one case and between *DT* and *OR* in the other. It is evident from the diagram that the drop on one phase is considerably greater than on the other. The difference varies with the power factor and the size of the wire, being greater with larger sizes of wire. No simple rule can be laid down for calculating such problems when the load is not equally balanced between phases and a graphical solution is usually the most practical. The proportions of Fig. 137 are based on three wires of the same size, the ohmic drop being taken at 15 per cent and the inductive drop at 10 per cent. This represents the approximate ratio of these components in a circuit of No. 2 wire strung 12 inches apart.

Where such a feeder carries an unbalanced load, the problem may be solved by calculating the drops on the three wires separately. The current on the neutral conductor is determined graphically by laying off the current in the phase wires to a suitable scale, along the lines *OA* and *OB* respectively. The resultant *ON* is then used as a base line from which to lay off the ohmic and inductive drops on the neutral wire. The drop is then found by measuring the differences $DZ - OX$ and $DT - OR$ by the use of the scale.

**Drop in Three-phase Circuits.** — In a three-phase circuit made up of three conductors symmetrically arranged in a triangle and carrying a balanced load, the inductive effect is the same in each wire and the calculation of drop may be made as easily as for a single-phase circuit.

The ohmic drop in each wire is in phase with its current, but as the currents in the three wires are 120 degrees apart the ohmic drop for the two wires making up any phase is not

twice that of one wire, as it is in the single-phase circuit, but is 1.73 times this drop. Likewise the inductive component, which is 90 degrees behind the current, is 1.73 times that of a single wire for the loop.

These values are readily found from the figures in Table XXII, and the known values of current, size of wire and length of circuit. The percentage may then be applied to the Mershon diagram.

For example, if the No. 0 circuit 4500 feet long carrying 100 amperes at 60 cycles and 12 inches separation were a three-wire three-phase circuit, the ohmic drop would be as in the single-phase circuit, $100 \times .098 \times 4.5 = 44$ volts per wire.

The drop in two wires of either phase would be $44 \times 1.73 = 76$ volts. This is $\frac{76}{2200} = 3.4$ per cent.

The inductive component *per wire* is $100 \times .104 \times 4.5 = 47$ volts, and for the loop $47 \times 1.73 = 81$ volts, or $\frac{81}{2200} = 3.7$ per cent.

Applying these percentages to the Mershon diagram we find the drop at 80 per cent power factor is 5 per cent of 2200, or 110 volts.

If the load in kilowatts on the three-phase circuit were the same as on the single-phase circuit, the current per wire on the three-phase circuit would be $\frac{100 \times 1.73}{3} = 58.0$ amperes, and the drop at 58 amperes on the three-phase circuit would be $\frac{58}{100}$ of 5 per cent, or 2.9 per cent.

The single-phase drop at the same load was found to be 5.8 per cent, or twice the three-phase drop.

Therefore for the same load and equal line drop, the size of the conductor in a three-phase circuit may be just half that of a single-phase circuit.

There being three wires in the three-phase circuit, it follows that the weight of copper required for a three-phase circuit

is three-quarters of that required for a single-phase transmission, other things being equal.

Therefore, if calculation shows that a certain sized conductor will carry a *given load* at a *given line drop*, *single phase*, it follows that *three* conductors of *one-half* that size will carry the *same* load at the *same drop*, *three phase*.

**Nonsymmetrical Arrangement.** — When the arrangement of conductors is not symmetrical, the inductive component is different between different pairs of wires, on account of the different distances between centers. The most common case is that in which the wires are arranged on a cross arm in

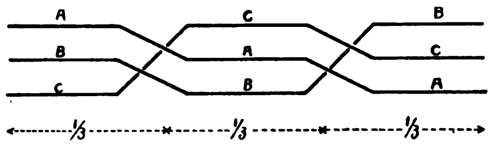



Fig. 138. Transposition of Three-phase Circuit.

the same horizontal plane, as is common practice in distribution circuits, and to some extent in transmission circuits. In such cases the equivalent of a symmetrical arrangement can be secured by transposing the conductors at proper intervals. Fig. 138 shows a circuit transposed at two points, so as to produce a complete spiral of the line. This is not required in 2200-volt distributing feeders which are equipped with line-drop compensators, as the compensation can easily be adjusted to correct unbalanced inductive conditions of this sort.

**Unbalanced Three-wire Three-phase Circuits.** — The calculations of drop in an unbalanced three-wire three-phase circuit is somewhat complicated and such problems are most readily solved graphically. Unbalanced loads which are not

more than 10 per cent from one another may usually be considered as balanced for practical purposes.

One of the most common conditions of this sort is found in systems where the lighting is all on one phase of the feeder and the third wire carries a small scattered load of three-phase power. Under these conditions the lighting phase may be considered as a single-phase circuit, as the current in the two conductors that make the lighting phase is much greater than it is in the other conductor, and the drop due to the lighting phase current is but little out of phase with the pressure which produces it.

However, as the power load increases the current in the conductors of the lighting phase pulls more and more out of phase with the lighting pressure, and the drop on the lighting phase becomes less and less for a given current value, until finally, when the current on the power phases equals that on the lighting phase, the drop on the lighting phase is but 86.6 per cent of what it would be with the same amount of current carried as lighting only.

That is, if 100 amperes on the lighting conductors produced a drop on the lighting phase of 10 per cent when there is no power load on the feeder, the drop with 100 amperes on each conductor will be only 8.66 per cent.

In practice this relation will not hold exactly, on account of the fact that the power factor of the lighting load is usually 95 per cent or higher, while that of the power load is 75 per cent to 80 per cent. This tends to make the current in one of the lighting phase conductors somewhat lower and that in the other lighting phase conductor somewhat higher than it would be if the power factor were the same in all phases. However, the reduction in the drop on the lighting phase is not sufficient ordinarily to interfere with the regulation of the lighting phase until the current on the power conductor reaches a point where it is more than 30 per cent of the average current on the lighting conductors.

**Four-wire Three-phase Line Drop.** — The working pressure at the receiving devices on such systems is the star pressure, that is, the pressure between phase wires and neutral. When the star pressure is 2200 volts, the pressure across phase wires is $2200 \times 1.73 = 3800$ volts.

With balanced load the neutral conductor carries no current and the drop is that in the phase wire only. The drop at 100 amperes on a No. 0 circuit 4500 feet long is $100 \times 4.5 \times .098 = 44$ volts. This is 2 per cent of 2200 volts. Likewise the inductive component is $100 \times 4.5 \times .104 = 47$ volts, or 2.1 per cent. At 80 per cent power factor, by the Mershon diagram the drop is 3 per cent.

As in the balanced three-wire circuit the size of wire for a given load and drop is just *half* what it would be for a *single-phase* circuit, and the *current* or *distance* may be halved and the calculation made as for a single-phase circuit if desired.

In the case of an unbalanced four-wire circuit, which is the more usual condition, the effect of the drop on the neutral wire must be taken into consideration. This varies with the proportion of unbalance and requires a graphical solution.

In general the effect of the unbalance is to increase the drop on the more heavily loaded phases and to make it less than it would be at balanced load on the lighter loaded phases.

The proportions of the diagram, Fig. 139, are based on calculations for a circuit having an ohmic drop of 15 per cent, an inductive drop of 10 per cent and loads on the three phases in the ratio of 60, 80 and 100, on $A$, $B$ and $C$ respectively.

The current $ON$ on the neutral conductor is the resultant of an unbalance of 20 on $B$ and 40 on $C$. This fixes the phase of the neutral current and hence of the drop in the neutral conductor. The triangle $OEF$ represents the ohmic and inductive components of the neutral drop.

This drop on the phase wires is represented by the triangle at the outer ends of the phase vectors. These are pro-

portional to the drop in the phase conductor (single distance only). The vector sum of the phase drop and of the neutral drop is the total loss of pressure at the end of the circuit. For instance, the net drop on *A* phase is the difference between the impressed pressure *EZ* and the delivered pressure *OX*. Similarly the drop on *B* phase is *ET* – *OR*, and that on *C* phase is *EW* – *OU*.

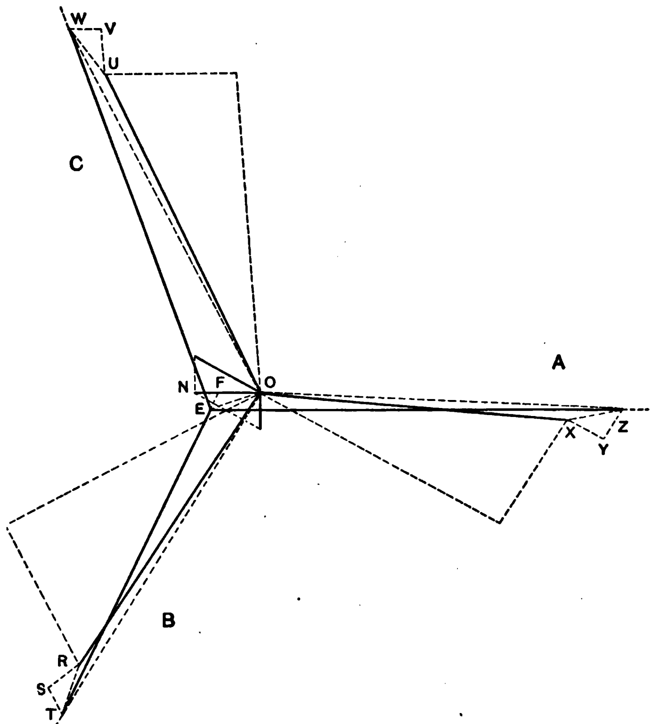



Fig. 139. Drop on Three-phase Four-wire Circuit.

Where line-drop compensators are employed in each conductor the only calculations required are those for the four individual conductors, and the use of a diagram to get the combined effect is unnecessary. The importance of equip-

ping the neutral conductor with a line-drop compensator is readily apparent from the diagram.

It is difficult to get accurate results from the diagram except when drawn to a large scale, and as the phase of the neutral current shifts hourly with different conditions of balance it is impossible to properly regulate unbalanced four-wire circuits by a schedule of volts and amperes, as is sometimes done with single-phase circuits.

**Mutual Induction.** — Where several alternating-current circuits are carried on the same poles there is an inductive reaction between them which is proportional to the current flowing and depends on the relative proximity of the circuits. That reaction is known as *mutual induction*, as the current in one circuit affects the voltage on the other, and *vice versa*. Mutual induction is a magnetic effect of the same nature as self-induction. The magnetic field due to the current in circuit *A* sets up an electromotive force in circuit *B* which is proportional to the volume of current in circuit *A* and the distance between them. Circuit *B*'s field affects circuit *A*'s pressure likewise. The electromotive force of mutual induction is a quarter cycle behind the current which produces it, and its phase must be taken into account in determining the effect.

The mutual induction voltages are so small at the ordinary current values at primary distributing voltages that they can be neglected, but where distribution is effected by means of circuits operating at voltages less than 300 which involve heavy currents, mutual induction is likely to be very troublesome. Its effect can be largely offset by making the distance between circuits as large as possible and by so arranging the conductors that as little of the magnetic flux of one circuit may be linked with another as possible. Circuits may also be transposed at intervals, so that the mutual induction set

up in one part of the circuit is offset by the mutual induction in the opposite sense in another section of the circuit.

With three-phase circuits this should be done twice, so as to make a complete spiral turn of the three wires.

The effect of a transmission line on a telephone circuit run parallel to it is usually such that numerous transpositions must be made in the telephone circuit to prevent inductive disturbances which make the telephone line noisy.

Underground circuits run in separate ducts are not usually sufficiently affected to make any appreciable disturbance.

**Skin Effect.** — Another condition which affects the pressure drop on alternating-current circuits is known as the *skin effect.* This is found in cables of large cross-section and is due to the fact that the current passing through the strands around the outer surface of the cable induces a pressure in the strands near the center which opposes the flow of current and causes the outer strands to carry the greater part of the load of the cable. In very large cables the current in the center strands is found to be so small that it is desirable to build up large cables about a core of nonconducting fibrous material. This puts the working metal near the outer layer and makes a more economical cable. Tables over 500,000 c.m. are often made in this manner where they are to be used on 60-cycle current, and over 1,000,000 c.m. on 25 cycles.

The rule for the calculation of the skin effect is a quite complicated one, as it involves the frequency, area of conductor, permeability of metal, temperature coefficient, etc. It is sufficient for all practical purposes to know that the skin effect is proportional to the product of the frequency by the circular mils. The higher this product, the more the resistance of the cable is increased by the skin effect. The resistance factors

corresponding to various values of circular mils and frequency are given in Table XXII. To determine the skin effect of a cable having an area of 1,000,000 c.m., carrying current at 60 cycles, refer to Table XXII opposite the product 60,000,000. The resistance factor is 1.096. The resistance of 1,000,000 c.m. cable to direct current at 68 degrees F. being .0103, the effective resistance is .0103 × 1.096 = .01129 when the cable carries alternating current at a frequency of 60 cycles. The resistance drop is increased 9.6 per cent by the skin effect in this size of cable.

TABLE XXII. — SKIN-EFFECT COEFFICIENTS.

| Cir. mils × frequency. | Coefficient. | | Cir. mils × frequency. | Coefficient. | |
|---|---|---|---|---|---|
| | Copper. | Aluminum. | | Copper. | Aluminum. |
| 10,000,000 | 1.000 | 1.000 | 80,000,000 | 1.158 | 1.069 |
| 20,000,000 | 1.008 | 1.000 | 90,000,000 | 1.195 | 1.085 |
| 30,000,000 | 1.025 | 1.006 | 100,000,000 | 1.23 | 1.104 |
| 40,000,000 | 1.045 | 1.015 | 125,000,000 | 1.332 | 1.151 |
| 50,000,000 | 1.07 | 1.026 | 150,000,000 | 1.433 | 1.206 |
| 60,000,000 | 1.096 | 1.04 | 175,000,000 | 1.53 | 1.266 |
| 70,000,000 | 1.126 | 1.053 | 200,000,000 | 1.622 | 1.33 |

**Electrostatic Capacity.** — Alternating-current circuits are subject to electrostatic-capacity phenomena which have an important bearing at the higher transmission voltages and frequencies. A line is charged and recharged with each alternation of the voltage. A charging current flows in such a circuit, which is proportional to the rate of change of the impressed voltage. The rate of change being greatest when the electromotive force wave is passing through zero, the charging current is at its maximum at that instant, and therefore is one-quarter cycle ahead of the impressed voltage wave. The charging current is a half cycle ahead of the inductive component, which is a quarter cycle behind the voltage wave,

and therefore tends to neutralize the effect of self-induction. At ordinary distributing voltages and frequencies the capacity effect is too small to be of any consequence in the solution of line-drop problems and need not be considered.

At transmission voltages and distances it becomes a matter of considerable importance at times.

The charging current of a circuit varies with its electrostatic capacity, its length and the voltage and frequency at which it is operated.

The capacity of an overhead circuit is fixed by the distance between the conductors and by their size. With insulated conductors surrounded by a lead sheath, the capacity is also affected by the dielectric constant of the insulating material.

The capacity of a single-phase circuit strung in the open air per 1000 feet of circuit is $C = \dfrac{.003677}{\log \dfrac{D}{r}}$ microfarads, when $D$ is the distance between centers of conductors and $r$ is half the diameter of the conductor. The logarithm is the common logarithm.

**Calculation of Charging Current.** — The charging current of a single-phase circuit is $I = \dfrac{6.28\,dfCE}{1{,}000{,}000}$ amperes, when $d$ is the distance in thousands of feet, $f$ is the frequency, $C$ is the capacity and $E$ is the voltage between conductors.

For example, in a circuit consisting of two No. 0 B. & S. wires strung 60 inches apart, 200,000 feet in length and operated at 40,000 volts, and 60 cycles, the charging current would be

$$I = \frac{6.28 \times 200 \times 60 \times C \times 40{,}000}{1{,}000{,}000} \text{ amperes.}$$

$$C = \frac{.003677}{\log \dfrac{D}{r}} = \frac{.003677}{\log \dfrac{60}{.162}} = .00143,$$

whence

$$I = \frac{6.28 \times 200 \times 60 \times .00143 \times 40{,}000}{1{,}000{,}000} = 4.3 \text{ amperes.}$$

The charging current of a three-phase circuit is $\frac{2}{\sqrt{3}}$ times that of a similar single-phase circuit at the same voltage and frequency.

That is, if the No. 0 circuit above referred to were a three-phase circuit operating at 40,000 volts with conductors equally spaced, the charging current would be

$$I = \frac{2 \times 4.3}{1.73} = 4.96 \text{ amperes.}$$

The ratio of $\frac{2}{1.73}$ is 1.155, and it is therefore useful to bear in mind the fact that the charging current of a three-phase circuit is 15.5 per cent greater than for a similar single-phase circuit.

The charging current of 4.96 amperes on the three-phase line would require $\frac{4.96 \times 3 \times 40{,}000}{1.73 \times 1000} = 344$ K.V.A. of generator capacity to charge the line when no load was being delivered.

When an inductive load is being delivered the lagging component of the load tends to offset the leading current required to charge the line. In this case it would require a lagging component of 344 K.V.A. to bring the power factor to 100 per cent.

An inductive load of 80 per cent power factor has a 60 per cent inductance factor. 344 is 60 per cent of 573 K.V.A. Hence an inductive load of 573 K.V.A. at 80 per cent power factor at the point of delivery would produce a power factor of 100 per cent at the generating station.

The line current leaving the generating station under these conditions would be about 80 per cent of that entering the

step-down transformers at the point of delivery. The line drop is therefore somewhat less than it would be without the charging current, and somewhat greater than it would be if the power factor were 100 per cent at both ends of the line. At higher power factors the wattless current is a smaller proportion and the load required to bring the power factor up to 100 per cent at the generator is greater. The charging current per 1000 feet of wire at 1000 volts three-phase line pressure is given in Table XXIII for 60 cycles. The values at other voltages or frequencies are proportionately higher. At 40,000 volts, the values in the tables should be multiplied by 40, or at 25 cycles they are $\frac{25}{60}$ of those in the table.

TABLE XXIII. — CHARGING CURRENT THREE-PHASE CIRCUITS IN AIR.

| Size of conductor. | Amperes per 1000 feet, per 1000 volts, at 60 cycles. | | | | | | |
|---|---|---|---|---|---|---|---|
| | Distance between centers. | | | | | | |
| | $\frac{3}{4}$ in. | 1 in. | 24 in. | 36 in. | 48 in. | 60 in. | 72 in. |
| 350,000 | ...... | ...... | .000867 | .000788 | .000745 | .00071 | .000688 |
| 0,000 | .00312 | .0025 | .000819 | .000749 | .000710 | .000679 | .000658 |
| 000 | .00284 | .00233 | .000797 | .000732 | .000693 | .000666 | .000645 |
| 00 | .0026 | .00216 | .000775 | .000714 | .000679 | .000649 | .000632 |
| 0 | .00241 | .00202 | .000758 | .000701 | .000662 | .000640 | .000618 |
| 1 | .00224 | .0019 | .000740 | .000684 | .000649 | .000623 | .000605 |
| 2 | .00209 | .0018 | .000719 | .000666 | .000636 | .00061 | .000592 |
| 4 | .00185 | .00161 | .000688 | .000640 | .00061 | .000588 | .000571 |
| 6 | .00165 | .00146 | .000645 | .000605 | .000575 | .000557 | .000544 |
| 8 | .00150 | .00134 | .000623 | .000579 | .000557 | .000540 | .000523 |
| 10 | .00137 | .00124 | .000597 | .000562 | .000536 | .000523 | .000510 |

The tendency of the charging current to raise the power factor of the line current tends to reduce the line drop where the load is of an inductive character. With very long lines and high voltages, it is not unusual to have a line charging current so high that the power factor is a leading one most of the time. With an 80-mile line operating at 60,000 volts, 60 cycles, it requires an inductive load of about 2800 K.V.A.

at 80 per cent power factor to neutralize the line charging current. At loads less than 3000 K.V.A. the power factor would be leading and the inductive component of the line drop would tend to raise the power factor. The charging current of long high-voltage lines places restrictions upon the size of the generating and transforming equipment in some cases. For instance, a generating station supplying an 80-mile 60,000-volt line should not have a generator rated at less than 1500 to 2000 K.V.A., as the line charging current is about 1600 K.V.A. and it would be impossible to excite the line at full pressure from a smaller machine running singly without overloading it.

**Charging Current of Cables.** — In underground cable work the effect of charging current is greatly increased by the reduced separation of polarities while the inductive effect is correspondingly decreased thereby. The charging current cannot be determined so easily, however, as in the case of the overhead line, since the dielectric in the cable is not air and the dielectric constant of the insulation must be taken into account. The formula for the capacity of a three-phase three-conductor cable in one lead sheath is more complex than that for overhead lines. The capacity per 1000 feet of cable is

$$C = \frac{.00735\,K}{\log \dfrac{3\,a^2\,(R^2 - a^2)^3}{r^2\,(R^6 - a^6)}} \text{ microfarads,}$$

when $K$ is the dielectric constant, $a$ is the distance from the center of the cross-section of the cable to the center of the conductors, $R$ is the radius of the inside of the lead sheath and $r$ is the radius of the conductor.

The charging current is $I = \dfrac{2 \times 6.28\, fCEL}{1.73 \times 1{,}000{,}000}$, as in the case of the three-phase overhead line.

**Dielectric Constants.** — The value of $K$, the dielectric constant in such calculations, must be determined experimentally by tests on samples of cable. It varies with different materials and with variation of temperature with the same material. In paper cable the different oils used to impregnate the paper are likely to have different constants.

The value of the dielectric constant of air is 1, that of vulcanized rubber is 3.5, manila paper, dry, is 1.8, manila paper and resin oil is 2.4, and varnished cambric is 3.5. The effect of temperature on the three principal kinds of cable insulation is shown in Table XXIV. This table contains coefficients by which the value of dielectric constants should be multiplied as the temperature rises above 60 degrees F. The general effect of increase in temperature is to decrease the dielectric constant and therefore the charging current.

TABLE XXIV.—VARIATION OF DIELECTRIC CONSTANT WITH TEMPERATURE.

| | Temperature coefficients. | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Temperature F. | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 140 |
| Oiled paper...... | 1.00 | .89 | .75 | .60 | .46 | .34 | .25 | .14 |
| Varnished cloth . | 1.00 | .90 | .79 | .70 | .60 | .50 | .42 | .31 |
| Rubber ......... | 1.00 | .97 | .93 | .89 | .84 | .80 | .76 | .66 |

The length and voltage of cable systems is usually such that the charging current is not sufficient to cause any operating inconvenience. In the 25-cycle 9000-volt system of the Chicago central station company the charging current of the three-conductor 4/0 cable is about .24 ampere per mile per conductor, or 24 amperes per 100 miles. This amounts to $\frac{24 \times 9000 \times 3}{1.73 \times 1000} = 370$ K.V.A. per 100 miles, or something over 1500 K.V.A. for the entire system, which embodies over 400

miles of transmission cable. The generating units are so large and the load so great compared with this that the charging current does not cause any inconvenience.

With 20,000-volt 60-cycle cables the charging current is about four times that of the 25-cycle cable above cited and becomes noticeable in a large system.

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